# Module I

# Course Overview
# And
# Introduction To Operating Systems

# COURSE MOTIVATION AND SCOPE

# Scope

This is a course about the design and structure of computer operating systems. It covers the concepts, principles, functionality, tradeoffs, and implementation of systems that support concurrent processing.

# What We Will Cover

- Operating system fundamentals
- Functionality an operating system offers
- Major system components
- Interdependencies and system structure
- The key relationships between operating system abstractions and the underlying hardware (especially processes and interrupts)
- A few implementation details and examples

# What You Will Learn

- Fundamental
  - Principles
  - Design options
  - Tradeoffs
- How to modify and test operating system code
- How to design and build an operating system

# What We Will NOT Cover

- A comparison of large commercial and open source operating systems
- A description of features or instructions on how to use a particular commercial system
- A survey of research systems and alternative approaches that have been studied
- A set of techniques for building operating systems on unusual hardware

# How Operating Systems Changed Programming

- Before operating systems
  - Only one application could run at any time
  - The application contained code to control specific I/O devices
  - The application had to overlap I/O and processing
- Once an operating system was in place
  - Multiple applications could run at the same time
  - An application is not built for specific I/O devices
  - A programmer does not need to overlap I/O and processing
  - An application is written without regard to other applications

# Why Operating Systems Are Difficult To Build

- The gap between hardware and high-level services is huge
  - Hardware is ugly
  - Operating system abstractions are beautiful
- Everything is now connected by computer networks
  - An operating system must offer communication facilities
  - Distributed mechanisms (e.g., remote file access) are more difficult to create than local mechanisms

# An Observation About Efficiency

- Our job in Computer Science is to build beautiful new abstractions that programmers can use
- It is easy to imagine magical new abstractions
- The hard part is that we must find abstractions that map onto the underlying hardware efficiently
- We hope that hardware engineers eventually build hardware for our abstractions (or at least build hardware that makes out abstractions more efficient)

# The Once And Future Hot Topic

- In the 1970s and early 1980s, operating systems was one of the hottest topics in CS
- By the mid-1990s, OS research had stagnated
- Now things have heated up again, and new operating systems are being designed for
  - Smart phones
  - Multicore systems
  - Data centers
  - Large and small embedded devices (the Internet of Things)

# XINU AND THE LAB

# Motivation For Studying A Real Operating System

- Provides examples of the principles
- Makes everything clear and concrete
- Shows how abstractions map to current hardware
- Gives students a chance to experiment and gain first-hand experience

# Can We Study Commercial Systems?

- Windows
  - Millions of line of code
  - Proprietary
- Linux
  - Millions of line of code
  - Lack of consistency across modules
  - Duplication of functionality with slight variants

# An Alternative: Xinu

- Small — can be read and understood in a semester
- Complete — includes all the major components
- Elegant — provides an excellent example of clean design
- Powerful — has dynamic process creation, dynamic memory management, flexible I/O, and basic Internet protocols
- Practical — has been used in real products

# The Xinu Lab

- Innovative facility for rapid OS development and testing
- Allows each student to create, download, and run code on bare hardware
- Completely automated
- Handles hardware reboot when necessary
- Provides communication to the Internet as well as among computers in the lab

# How The Xinu Lab Works

- A student
  - Logs into a conventional desktop system called a *front-end*
  - Modifies and compiles a version of the Xinu OS
  - Requests a computer to use for testing
- Lab software
  - Allocates one of the *back-end* computers for the student to use
  - Downloads the student’s Xinu code into the back-end
  - Connects the console from the back-end to the student’s window
  - Allows the student to release the back-end for others to use

# REQUIRED BACKGROUND
# AND PREREQUISITES

# Background Needed

- A few concepts from earlier courses
  - I/O: you should know the difference between standard library functions (e.g., *fopen*, *putc*, *getc*, *fread*, *fwrite*) and system calls (e.g., *open*, *close*, *read*, *write*)
  - File systems and hierarchical directories
  - Symbolic and hard links
  - File modes and protection
- Concurrent programming experience: you should have written a program that uses *fork* or *threads*

# Background Needed
## (continued)

- An understanding of runtime storage components
  - Segments (text, data, and bss) and their layout
  - Runtime stack used for function call; argument passing
  - Basic heap storage management (malloc and free)
- C programming
  - At least one nontrivial program
  - Comfortable with low-level constructs (e.g., bit manipulation and pointers)

# Background Needed
## (continued)

- Working knowledge of basic UNIX tools (needed for programming assignments)
  - Text editor (e.g., emacs)
  - Compiler / linker / loader
  - Tar archives
  - Make and Makefiles
- Desire to learn

# Course Syllabus

**See the handout**

**or**

**download from blackboard**

# How We Will Proceed

- We will examine the major components of an operating system
- For a given component we will
  - Outline the functionality it provides
  - Understand principles involved
  - Study one particular design choice in depth
  - Consider implementation details and the relationship to hardware
  - Quickly review other possibilities and tradeoffs
- Note: we will cover components in a linear order that allows us to understand one component at a time without relying on later components

# Questions?

# A FEW THINGS TO THINK ABOUT

**Perfection [in design] is achieved not when there is nothing to add, but rather when there is nothing more to take away.**

*– Antoine de Saint-Exupery*

**Real concurrency — in which one program actually continues to function while you call up and use another — is more amazing but of small use to the average person. How many programs do you have that take more than a few seconds to perform any task?**

*(From an article about new operating systems for the IBM PC in the New York Times, 25 April 1989)*

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# Introduction To Operating Systems (Definitions And Functionality)

# What Is An Operating System?

- Answer: a large piece of sophisticated software that provides an abstract computing environment
- An OS manages resources and supplies computational services
- An OS hides low-level hardware details from programmers
- Note: operating system software is among the most complex ever devised

# Example Services An OS Supplies

- Support for concurrent execution (multiple apps running at the same time)
- Process synchronization
- Process-to-process communication mechanisms
- Process-to-process message passing and asynchronous events
- Management of address spaces and virtual memory support
- Protection among users and running applications
- High-level interface for I/O devices
- File systems and file access facilities
- Internet communication

# What An Operating System Is NOT

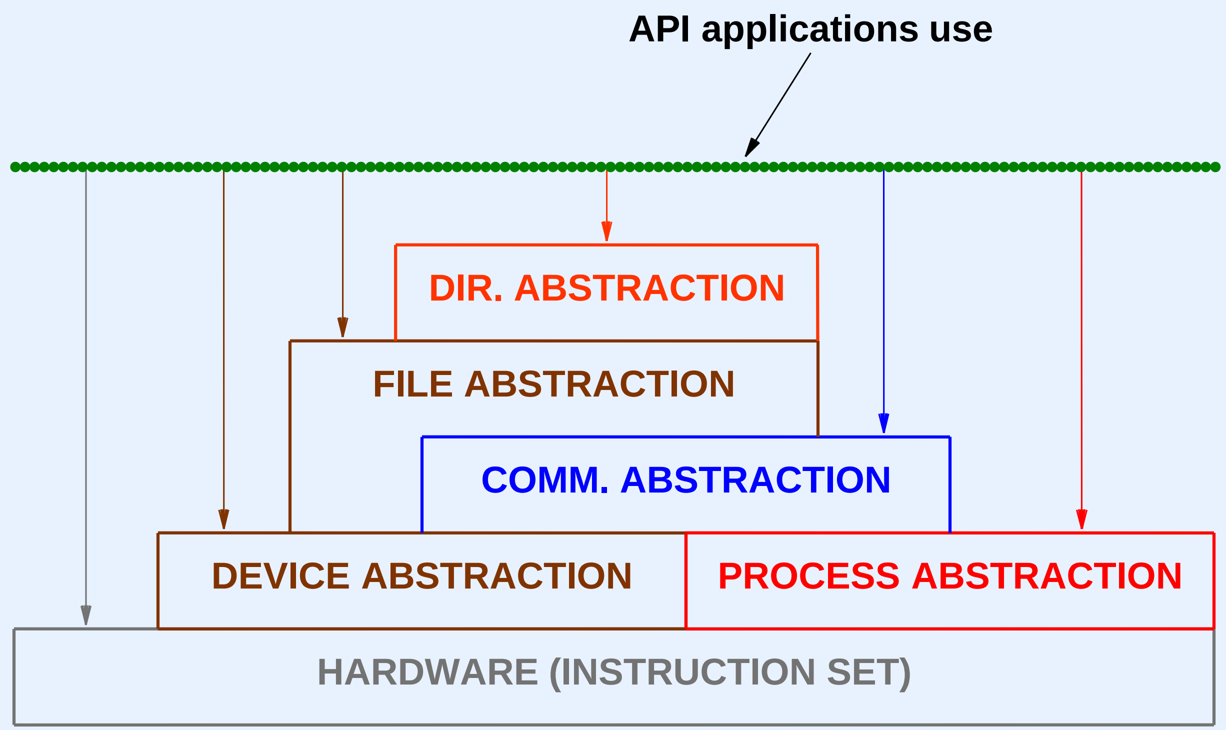
- A hardware mechanism
- A programming language
- A compiler
- A windowing system or a browser
- A command interpreter
- A library of utility functions
- A graphical desktop

# AN OPERATING SYSTEM
# FROM THE OUTSIDE

# The System Interface

- A single copy of the OS runs at any time
  - Hidden from users
  - Accessible only to application programs
- The *Application Program Interface (API)*
  - Defines services OS makes available
  - Defines arguments for the services
  - Provides access to OS abstractions and services
  - Hides hardware details

# OS Abstractions And The Application Interface




- Modules in the OS offer services to applications
- Internally, some services build on others

# Interface To System Services

- Appears to operate like a function call mechanism
  - OS makes set of “functions” available to applications
  - Application supplies arguments using standard mechanism
  - Application “calls” an OS function to access a service
- Control transfers to OS code that implements the function
- Control returns to caller when function completes

# Interface To System Services
## (continued)

- Requires a special hardware instruction to invoke an OS function
  - Moves from the application’s *address space* to OS’s address space
  - Changes from application *mode* or *privilege level* to OS mode
- Terminology used by various hardware vendors
  - *System call*
  - *Trap*
  - *Supervisor call*
- We will use the generic term *system call*

# An Example Of System Call In Xinu: Write A Character On The Console

```
/* ex1.c - main */

#include <xinu.h>

/*------------------------------------------------------------------------
 * main  -  Write "hi" on the console
 *------------------------------------------------------------------------
 */
void    main(void)
{
        putc(CONSOLE, 'h');
        putc(CONSOLE, 'i');
        putc(CONSOLE, '\n');
}
```

- Note: we will discuss the implementation of *putc* later

# OS Services And System Calls

- Each OS service accessed through system call interface
- Most services employ a set of several system calls
- Examples
  - Process management service includes functions to *suspend* and then *resume* a process
  - *Socket API* used for Internet communication includes many functions

# System Calls Used With I/O

- Open-close-read-write paradigm
- Application
  - Uses *open* to connect to a file or device
  - Calls functions to *write* data or *read* data
  - Calls *close* to terminate use
- Internally, the set of I/O functions coordinate
  - *Open* returns a descriptor, *d*
  - *Read* and *write* operate on descriptor *d*

# Concurrent Processing

- Fundamental concept that dominates OS design
- *Real concurrency* is only achieved when hardware operates in parallel
  - I/O devices operate at same time as processor
  - Multiple processors/cores each operate at the same time
- *Apparent concurrency* is achieved with *multitasking* (aka *multiprogramming*)
  - Multiple programs appear to operate simultaneously
  - The most fundamental role of an operating system

# How Multitasking Works

- User(s) start multiple computations running
- The OS switches processor(s) among available computations quickly
- To a human, all computations appear to proceed in parallel

# Terminology

- A *program* consists of static code and data
- A *function* is a unit of application program code
- A *process* (also called a *thread of execution*) is an active computation (i.e., the execution or “running” of a program)

# A Process

- Is an OS abstraction
- Can be created when needed (an OS system call allows a running process to create a new process)
- Is managed entirely by the OS and is unknown to the hardware
- Operates concurrently with other processes

# Example Of Process Creation In Xinu (Part 1)

```
/* ex2.c - main, sndA, sndB */

#include <xinu.h>

void    sndA(void), sndB(void);

/*------------------------------------------------------------------------
 * main  -  Example of creating processes in Xinu
 *------------------------------------------------------------------------
 */
void    main(void)
{
        resume( create(sndA, 1024, 20, "process 1", 0) );
        resume( create(sndB, 1024, 20, "process 2", 0) );
}

/*------------------------------------------------------------------------
 * sndA  -  Repeatedly emit 'A' on the console without terminating
 *------------------------------------------------------------------------
 */
void    sndA(void)
{
        while( 1 )
                putc(CONSOLE, 'A');
}
```

# Example Of Process Creation In Xinu (Part 2)

```
/*------------------------------------------------------------------------
 * sndB  -  Repeatedly emit ’B’ on the console without terminating
 *------------------------------------------------------------------------
 */
void    sndB(void)
{
        while( 1 )
                putc(CONSOLE, ’B’);
}
```

# The Difference Between Function Call And Process Creation

- A normal function call
  - Only involves a single computation
  - Executes synchronously (caller waits until the call returns)
- The *create* system call
  - Starts a new process and returns
  - Both the old process and the new process proceed to run after the call

# The Distinction Between A Program And A Process

- A sequential program is
  - Declared explicitly in the code (e.g., with the name *main*)
  - Is executed by a single thread of control
- A process
  - Is an OS abstractions that is not visible in a programming language
  - Is created independent of code that is executed
  - Important idea: multiple processes can execute the same code concurrently
- In the following example, two processes execute function *sndch* concurrently

# Example Of Two Processes Running The Same Code

```
/* ex3.c - main, sndch */

#include <xinu.h>

void    sndch(char);

/*------------------------------------------------------------------------
 * main  -  Example of 2 processes executing the same code concurrently
 *------------------------------------------------------------------------
 */
void    main(void)
{
        resume( create(sndch, 1024, 20, "send A", 1, 'A') );
        resume( create(sndch, 1024, 20, "send B", 1, 'B') );
}

/*------------------------------------------------------------------------
 * sndch  -  Output a character on a serial device indefinitely
 *------------------------------------------------------------------------
 */
void    sndch(
          char  ch              /* The character to emit continuously   */
        )
{
        while ( 1 )
                putc(CONSOLE, ch);
}
```

# Storage Allocation When Multiple Processes Execute

- Various memory models exist for concurrent processes
- Each process requires its own storage for
  - A runtime stack of function calls
  - Local variables
  - Copies of arguments passed to functions
- A process *may* have private heap storage as well

# Consequence For Programmers

A copy of function arguments and local variables is associated with each process executing a particular function, *not* with the code in which the variables and arguments are declared.

# AN OPERATING SYSTEM FROM THE INSIDE

# Operating System Properties

- An OS contains well-understood subsystems
- An OS must handle dynamic situations (processes come and go)
- Unlike most applications, an OS uses a heuristic approach
  - A heuristic can have corner cases
  - Policies from one subsystem can conflict with policies from others
- Complexity arises from interactions among subsystems, and the side-effects can be
  - Unintended
  - Unanticipated, even by the OS designer
- We will see examples

# Building An Operating System

- The intellectual challenge comes from the design of a “system” rather than from the design of individual pieces
- Structured design is needed
- It can be difficult to understand the consequences of individual choices
- We will study a hierarchical microkernel design that helps control complexity and provides a unifying architecture

# Major OS Components

- Process manager
- Memory manager
- Device manger
- Clock (time) manager
- File manager
- Interprocess communication system
- Intermachine communication system
- Assessment and accounting

# Our Multilevel Structure

- Organizes all components
- Controls interactions among subsystems
- Allows an OS to be understood and built incrementally
- Differs from a traditional layered approach
- Will be employed as the design paradigm throughout the text and course

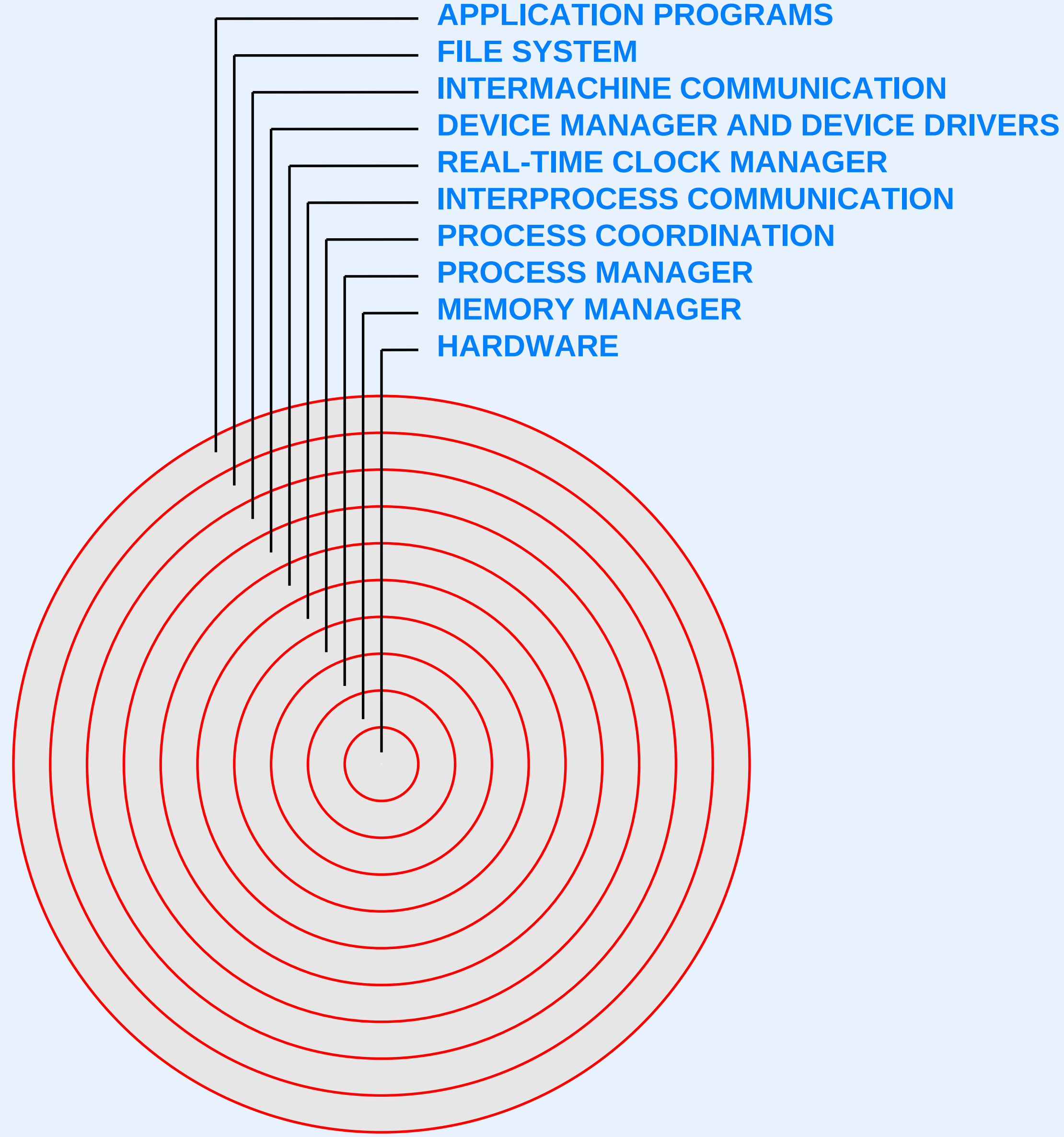
# Multilevel Vs. Multilayered Organization

- Multilayer structure
  - Visible to the user as well as designer
  - Software at a given layer only uses software at the layer directly beneath
  - Examples
    - Internet protocol layering
    - MULTICS layered security structure
- Can be extremely inefficient

# Multilevel Vs. Multilayered Organization
## (continued)

- Multilevel structure
  - Separates all software into multiple levels
  - Allows software at a given level to use software at *all* lower levels
  - Especially helpful during system construction
  - Focuses a designer's attention on one aspect of the OS at a time
  - Helps keeps policy decisions independent and manageable
  - Is efficient

# Multilevel Structure Of Xinu



# How To Understand An OS

- Use the same approach as when designing a system
- Work one level at a time
- Understand the service to be provided at the level
- Consider the overall *goal* for the service
- Examine the *policies* that are used to achieve the goal
- Study the *mechanisms* that enforce the policies
- Look at an *implementation* that runs on specific hardware

# A Design Example

- Example: access to I/ O
- Goal: “fairness”
- Policy: First-Come-First-Served access to a given I/O device
- Mechanism: a queue of pending requests (FIFO order)
- Implementation: program written in C

# LISTS OF PROCESSES

# Queues And Lists

- Keeping track of processes is fundamental throughout an operating system
- Various forms are needed
  - FIFO queues of processes
  - Lists of processes kept in priority order
  - Event lists ordered by the time of occurrence
- Operations required
  - Insert a process onto a list
  - Extract the “next” process from a list
  - Delete an arbitrary process

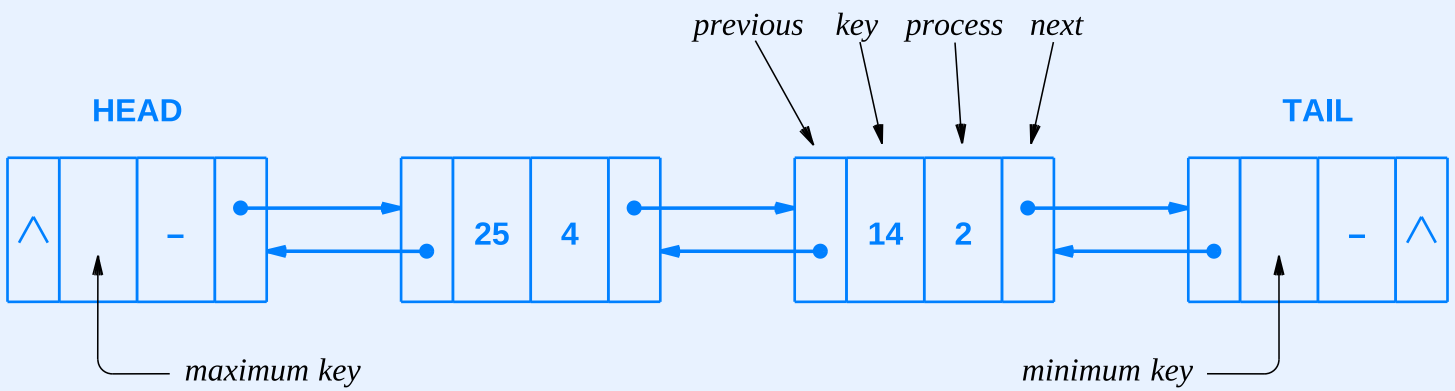
# Lists And Queues In Xinu

- Important ideas
  - A process is known by an integer *process ID*
  - A list of processes really stores a set of process IDs
- A single data structure can be used to store many types of process lists

# Unified List Storage in Xinu

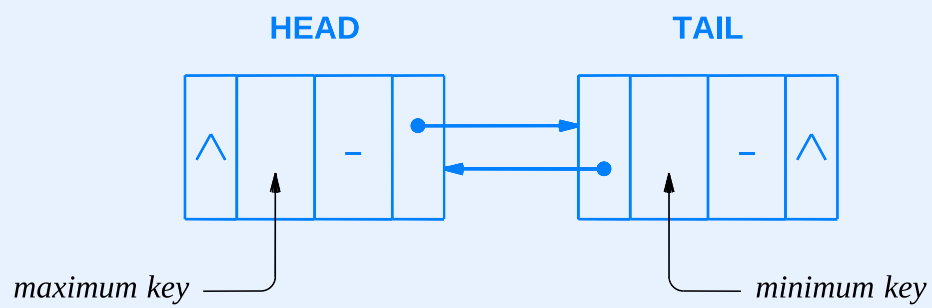
- All lists are doubly-linked, which means a node points to its predecessor and successor
- Each node stores a *key* as well as a process ID, even though the key is not used in a FIFO list
- Each list has a *head* and *tail*; the head and tail nodes have the same shape as other nodes
- Non-FIFO lists are always ordered in descending order according to the key values
- The key value in a head node is the maximum integer used as a key, and the key value in the tail node is the minimum integer used as a key

# Conceptual List Structure




- The example list contains two processes, 2 and 4
- Process 4 has key 25
- Process 2 has key 14

# Pointers In An Empty List




- In an empty list, the head and tail nodes are linked
- Having a head and tail eliminates special cases for insertion and deletion

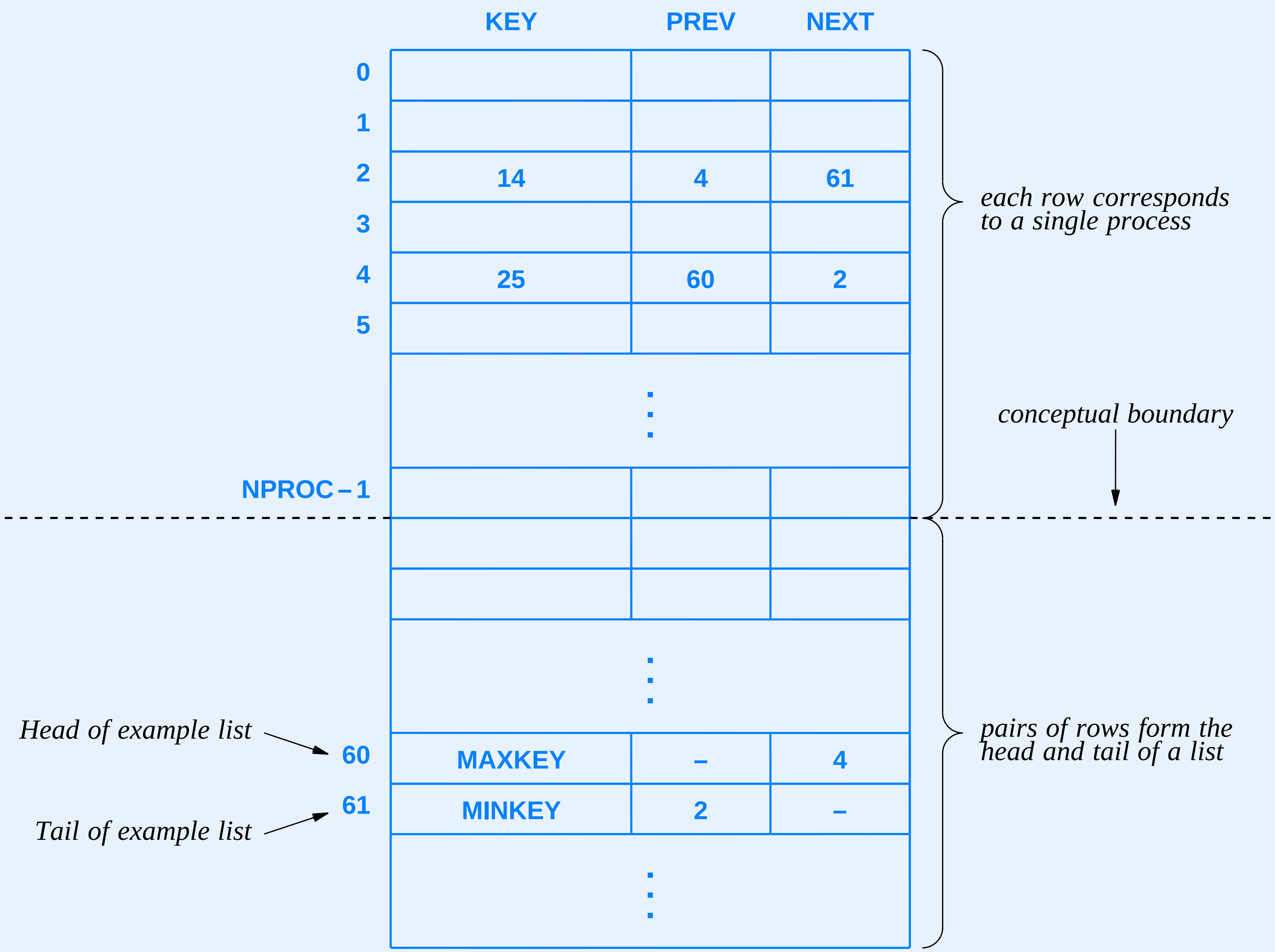
# Reducing The List Size

- Pointers can mean a large memory footprint, especially on a 64-bit computer
- Important concept: a process can appear on at most one list at any time
- Xinu uses two clever techniques to reduce the size of lists
  - Relative pointers instead of memory addresses
  - An implicit data structure

# Xinu List Optimizations

- Lists are stored in an array
  - Each item in the array is one node
  - Relative pointers; the array index is used to identify a node instead of an address
- Implicit data structure
  - Let *NPROC* be the number of processes in the system
  - Assign process IDs 0 through *NPROC – 1*
  - Let $i^{th}$ element of the array correspond to process *i*, for $0 \le i < NPROC$
  - Store heads and tails in same array at positions *NPROC* and higher

# An Illustration Of An Array Holding The Xinu List Structure



# Implementation

- A single array is used to hold all lists of processes
  - The array is global and available throughout the entire OS
  - The array is named *queuetab*
- Functions are available to manipulate lists
  - Include tests, such as *isempty*, as well as insertion and deletion operations
  - For efficiency, functions are implemented with inline macros when possible
- Example code shown after a discussion of types

# A Question About Types In C

- K&R C defined *short*, *int*, and *long* to be machine-dependent
- ANSI C left *int* as a machine-dependent type
- A programmer can define type names
- Question: should a type specify
  - The purpose of an item?
  - The size of an item?
- Example: should a process ID type be named
  - *processid_t* to indicate the purpose?
  - *int32* to indicate the size?

# Type Names Used In Xinu

- Xinu uses a compromise to encompass both purpose and size
- Example: consider a variable that holds an index into queuetab
- The type name can specify
  - That the variable is a queue table index
  - That the variable is a 16-bit signed integer
- Xinu uses the type name *qid16* to specify both
- Example declarations follow

# Definitions From queue.h (Part 1)

```
/* queue.h - firstid, firstkey, isempty, lastkey, nonempty          */

/* Queue structure declarations, constants, and inline functions       */

/* Default # of queue entries: 1 per process plus 2 for ready list plus */
/*                     2 for sleep list plus 2 per semaphore           */
#ifndef NQENT
#define NQENT   (NPROC + 4 + NSEM + NSEM)
#endif

#define EMPTY   (-1)            /* Null value for qnext or qprev index  */
#define MAXKEY  0x7FFFFFFF      /* Max key that can be stored in queue  */
#define MINKEY  0x80000000      /* Min key that can be stored in queue  */

struct  qentry  {               /* One per process plus two per list    */
        int32   qkey;           /* Key on which the queue is ordered    */
        qid16   qnext;          /* Index of next process or tail        */
        qid16   qprev;          /* Index of previous process or head    */
};

extern  struct qentry   queuetab[];
```

# Definitions From queue.h (Part 2)

```
/* Inline queue manipulation functions */

#define queuehead(q)    (q)
#define queuetail(q)    ((q) + 1)
#define firstid(q)      (queuetab[queuehead(q)].qnext)
#define lastid(q)       (queuetab[queuetail(q)].qprev)
#define isempty(q)      (firstid(q) >= NPROC)
#define nonempty(q)     (firstid(q) <  NPROC)
#define firstkey(q)     (queuetab[firstid(q)].qkey)
#define lastkey(q)      (queuetab[ lastid(q)].qkey)

/* Inline to check queue id assumes interrupts are disabled */

#define isbadqid(x)     (((int32)(x) < NPROC) || (int32)(x) >= NQENT-1)
```

# Code For Insertion And Deletion From A Queue (Part 1)

```
/* queue.c - enqueue, dequeue */

#include <xinu.h>

struct qentry   queuetab[NQENT];        /* Table of process queues      */

/*------------------------------------------------------------------------
 *  enqueue  -  Insert a process at the tail of a queue
 *------------------------------------------------------------------------
 */
pid32   enqueue(
          pid32         pid,            /* ID of process to insert      */
          qid16         q               /* ID of queue to use           */
        )
{
        qid16   tail, prev;             /* Tail & previous node indexes */

        if (isbadqid(q) || isbadpid(pid)) {
                return SYSERR;
        }

        tail = queuetail(q);
        prev = queuetab[tail].qprev;

        queuetab[pid].qnext  = tail;    /* Insert just before tail node */
        queuetab[pid].qprev  = prev;
        queuetab[prev].qnext = pid;
        queuetab[tail].qprev = pid;
        return pid;
}
```

# Code For Insertion And Deletion From A Queue (Part 2)

```
/*------------------------------------------------------------------------
 *  dequeue  -  Remove and return the first process on a list
 *------------------------------------------------------------------------
 */
pid32   dequeue(
          qid16         q               /* ID queue to use              */
        )
{
        pid32   pid;                    /* ID of process removed        */

        if (isbadqid(q)) {
                return SYSERR;
        } else if (isempty(q)) {
                return EMPTY;
        }

        pid = getfirst(q);
        queuetab[pid].qprev = EMPTY;
        queuetab[pid].qnext = EMPTY;
        return pid;
}
```

# Code For Insertion In An Ordered List (Part 1)

```
/* insert.c - insert */

#include <xinu.h>

/*------------------------------------------------------------------------
 *  insert  -  Insert a process into a queue in descending key order
 *------------------------------------------------------------------------
 */
status  insert(
          pid32         pid,              /* ID of process to insert     */
          qid16         q,                /* ID of queue to use          */
          int32         key               /* Key for the inserted process */
        )
{
        qid16   curr;                     /* Runs through items in a queue*/
        qid16   prev;                     /* Holds previous node index    */

        if (isbadqid(q) || isbadpid(pid)) {
                return SYSERR;
        }

        curr = firstid(q);
        while (queuetab[curr].qkey >= key) {
                curr = queuetab[curr].qnext;
        }
```

# Code For Insertion In An Ordered List (Part 2)

```
        /* Insert process between curr node and previous node */

        prev = queuetab[curr].qprev;    /* Get index of previous node   */
        queuetab[pid].qnext = curr;
        queuetab[pid].qprev = prev;
        queuetab[pid].qkey = key;
        queuetab[prev].qnext = pid;
        queuetab[curr].qprev = pid;
        return OK;
}
```

# Accessing An Item In A List (Part 1)

```
/* getitem.c - getfirst, getlast, getitem */

#include <xinu.h>

/*------------------------------------------------------------------------
 *  getfirst  -  Remove a process from the front of a queue
 *------------------------------------------------------------------------
 */
pid32   getfirst(
          qid16         q               /* ID of queue from which to    */
        )                               /* Remove a process (assumed    */
                                        /*   valid with no check)       */
{
        pid32   head;

        if (isempty(q)) {
                return EMPTY;
        }

        head = queuehead(q);
        return getitem(queuetab[head].qnext);
}
```

# Accessing An Item In A List (Part 2)

```
/*------------------------------------------------------------------------
 *  getlast  -  Remove a process from end of queue
 *------------------------------------------------------------------------
 */
pid32   getlast(
          qid16         q               /* ID of queue from which to    */
        )                               /* Remove a process (assumed    */
                                        /*   valid with no check)       */
{
        pid32 tail;

        if (isempty(q)) {
                return EMPTY;
        }

        tail = queuetail(q);
        return getitem(queuetab[tail].qprev);
}
```

# Accessing An Item In A List (Part 3)

```
/*------------------------------------------------------------------------
 *  getitem  -  Remove a process from an arbitrary point in a queue
 *------------------------------------------------------------------------
 */
pid32   getitem(
          pid32         pid             /* ID of process to remove      */
        )
{
        pid32   prev, next;

        next = queuetab[pid].qnext;     /* Following node in list       */
        prev = queuetab[pid].qprev;     /* Previous node in list        */
        queuetab[prev].qnext = next;
        queuetab[next].qprev = prev;
        return pid;
}
```

# Allocating A New List

```
/* excerpt from newqueue.c */

qid16   newqueue(void)
{
        static qid16    nextqid=NPROC;  /* Next list in queuetab to use */
        qid16           q;              /* ID of allocated queue        */

        q = nextqid;
        if (q > NQENT) {                /* Check for table overflow     */
                return SYSERR;
        }

        nextqid += 2;                   /* Increment index for next call*/

        /* Initialize head and tail nodes to form an empty queue */

        queuetab[queuehead(q)].qnext = queuetail(q);
        queuetab[queuehead(q)].qprev = EMPTY;
        queuetab[queuehead(q)].qkey  = MAXKEY;
        queuetab[queuetail(q)].qnext = EMPTY;
        queuetab[queuetail(q)].qprev = queuehead(q);
        queuetab[queuetail(q)].qkey  = MINKEY;
        return q;
}
```

# Summary

- An operating system supplies a set of services
- System calls provide interface between OS and application
- Concurrency is fundamental concept
  - Between I/O devices and processor
  - Between multiple computations
- A process is OS abstraction for concurrency; it does not appear in the code
- A process differs from program or function
- You will learn how to design and implement system software that supports concurrent processing

# Summary
## (continued)

- An OS has well-understood internal components
- Complexity arises from interactions among components
- A multilevel approach helps organize system structure
- OS design involves inventing policies and mechanisms that enforce overall goals
- Xinu includes a compact list structure that uses relative pointers and an implicit data structure to reduce size
- Xinu type names specify both purpose and data size

Questions?