4. Threads

ECE30021/ITP30002 Operating Systems

Agenda

- Overview
- Multithreading models
- Thread libraries
- Threading issues
- Operating system examples

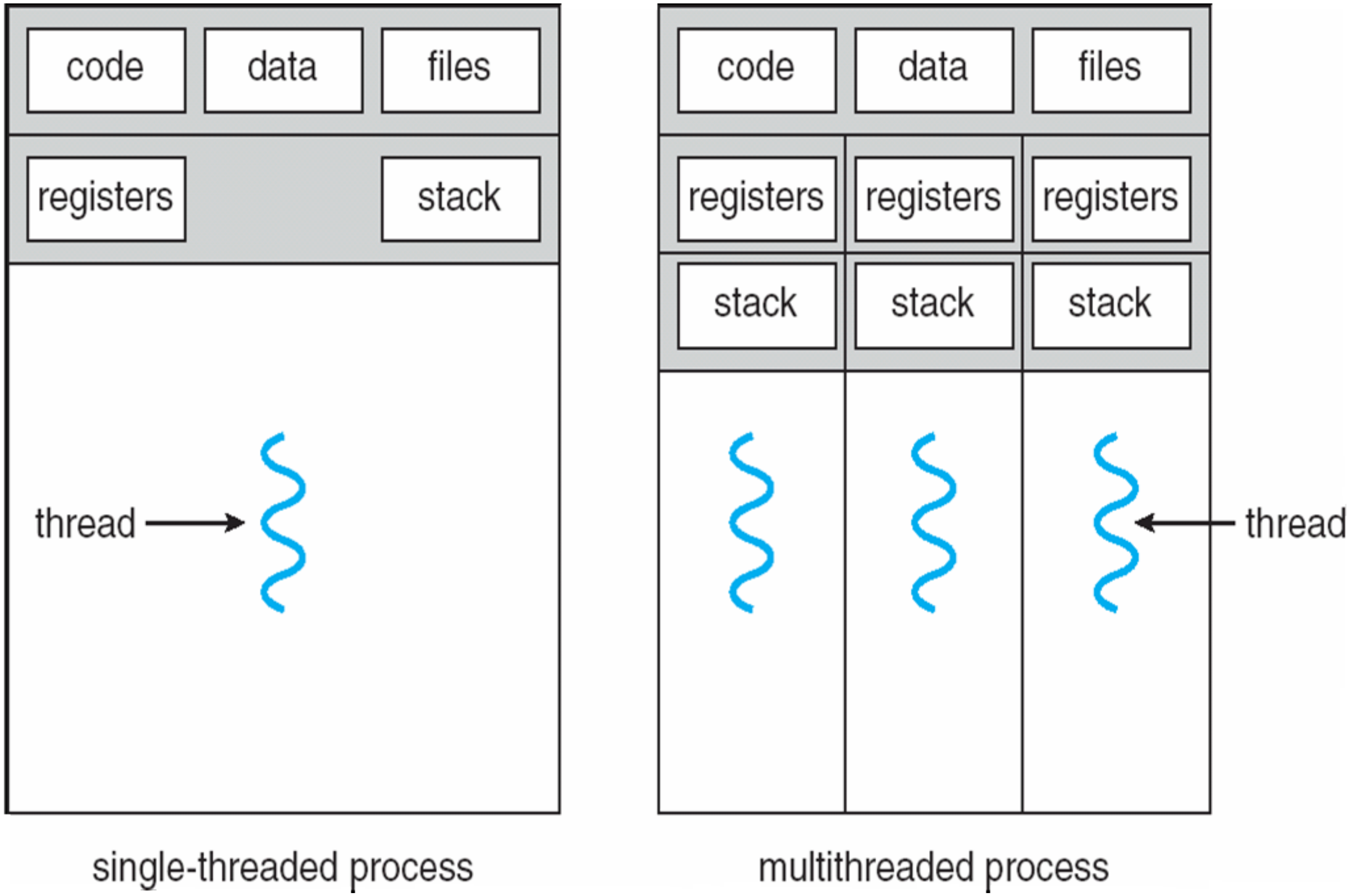
Motivation

- Most modern applications are multithreaded
- Threads run within application
- Multiple tasks with the application can be implemented by separate threads
  - Update display, fetch data, spell checking, answer a network request
- Process creation is heavy-weight while thread creation is light-weight
- Can simplify code, increase efficiency
- Kernels are generally multithreaded

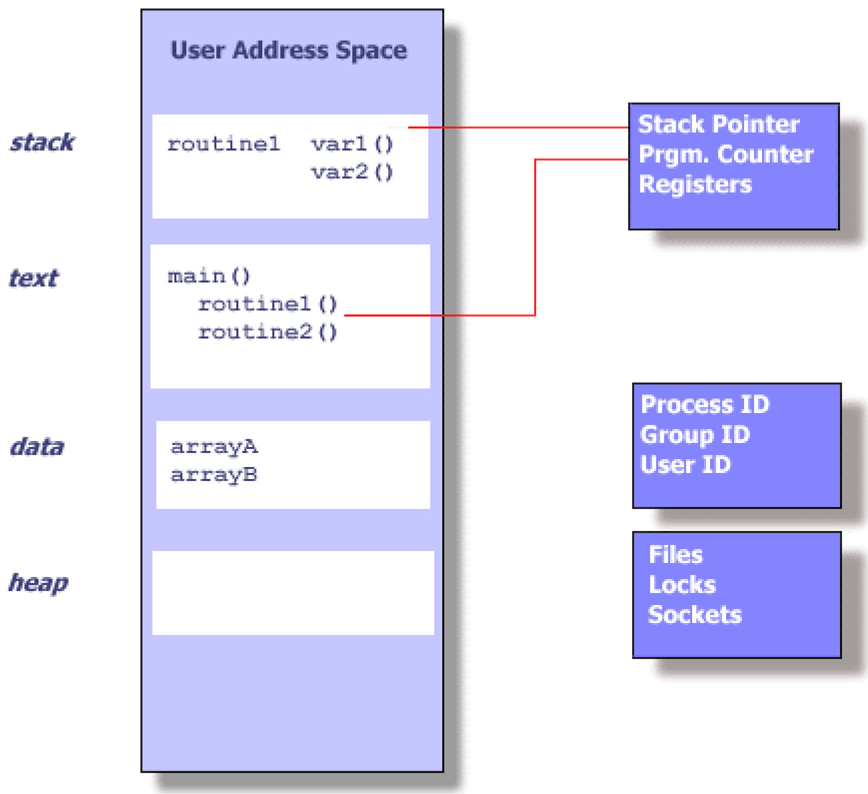
Overview

- Process: program in execution
  - Each process occupies resources required for execution
- Thread: a way for a program to split itself into two or more simultaneously running tasks
  - Smaller unit than process
  - Threads in a process share resources
- A thread is comprised of
  - Thread ID, program counter, register set, stack, etc.

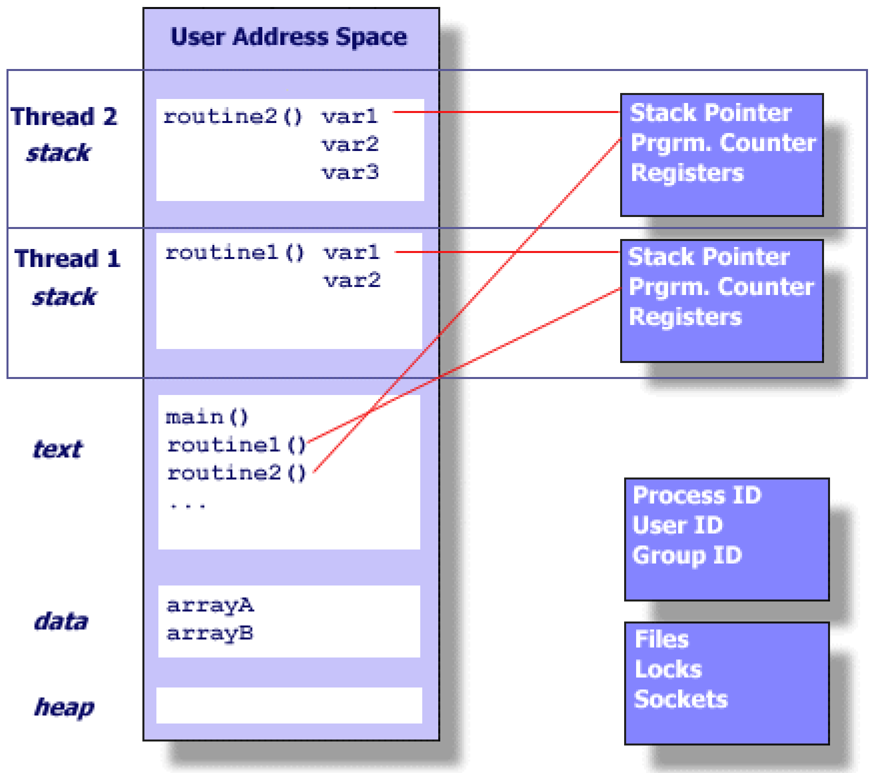
Multithreaded Process



Process vs. Thread



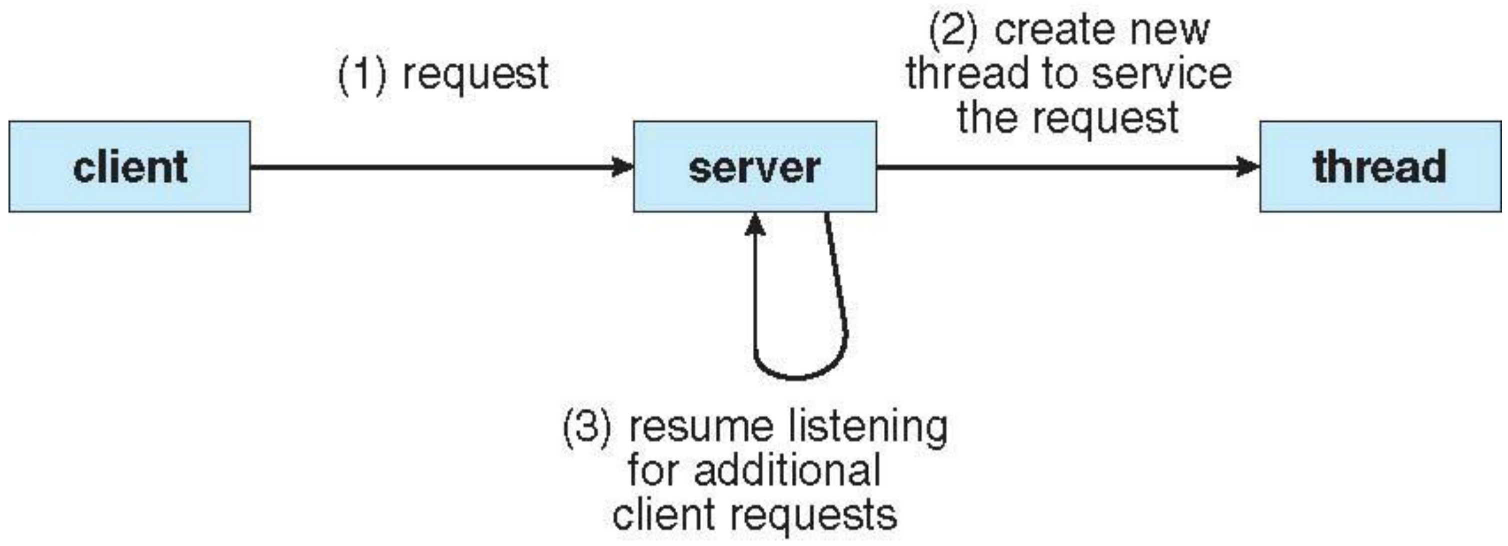
Single-threaded process



Multi-threaded Process

Why Thread?

- Process creation is expensive in time and resource
  - Ex) Web server accepting thousands of requests



Why Thread?

- Advantages of multithreaded programming
  - Responsiveness
  - Resource sharing
  - Economy
    - Creating process is about 30 times slower than creating thread
  - Scalability
    - Utilization of multiprocessor architectures

Multicore Programming

- Multicore or multiprocessor systems putting pressure on programmers, challenges include:
  - Dividing activities
  - Balance
  - Data splitting
  - Data dependency
  - Testing and debugging

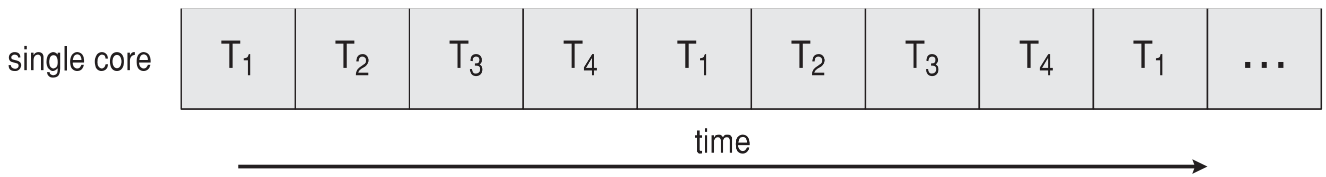
Multicore Programming (Cont.)

- Types of parallelism
  - Data parallelism – distributes subsets of the same data across multiple cores, same operation on each
  - Task parallelism – distributing threads across cores, each thread performing unique operation
- As # of threads grows, so does architectural support for threading
  - CPUs have cores as well as hardware threads
  - Consider Oracle SPARC T4 with 8 cores, and 8 hardware threads per core

Concurrency vs. Parallelism

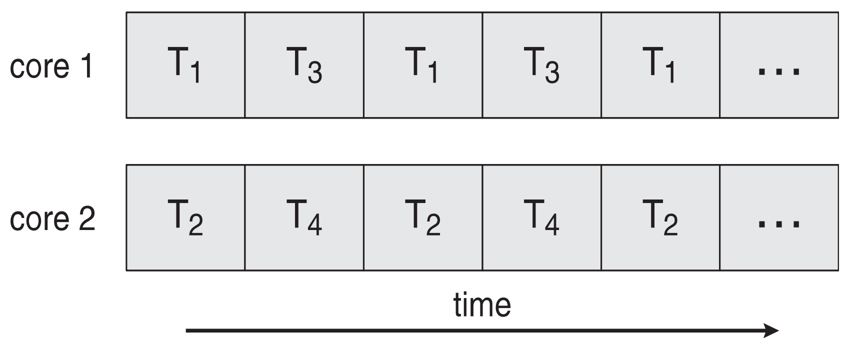
- Concurrency supports more than one task making progress
  - Single processor / core, scheduler providing concurrency

  Ex) Concurrent execution on single-core system:



- Parallelism implies a system can perform more than one task simultaneously

  Ex) Parallelism on a multi-core system:



Amdahl's Law

- Identifies performance gains from adding additional cores to an application that has both serial and parallel components
  - S is serial portion, N processing cores

$$speedup \leq \frac{1}{S + \frac{(1-S)}{N}}$$

  Ex) Application is 75% parallel / 25% serial, moving from 1 to 2 cores results in speedup of 1.6 times

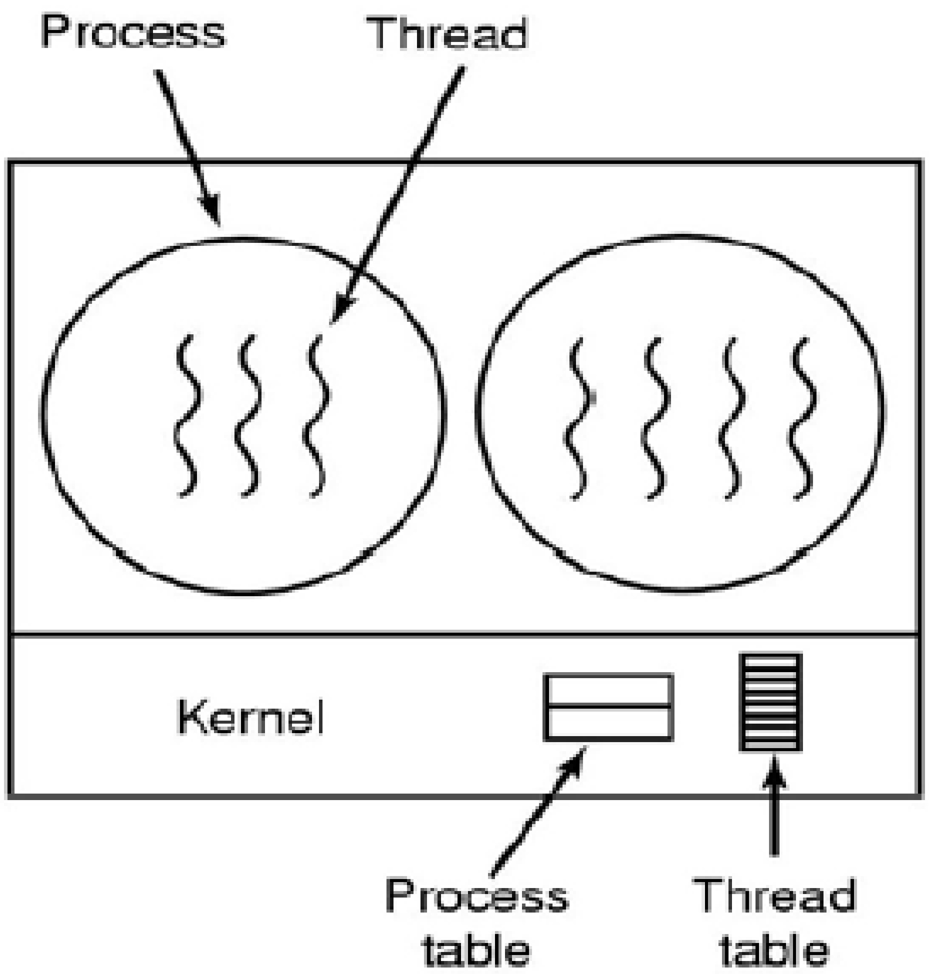
  - As N approaches infinity, speedup approaches 1 / S
  - Serial portion of an application has disproportionate effect on performance gained by adding additional cores.

Types of Thread

- User thread: thread supported by thread library in user level
  - Created by library function call (not system call)
  - Kernel is not concerned in user thread.
  - Switching of user thread is faster than kernel thread.

- Kernel thread: thread supported by kernel
  - Created and managed by kernel
  - Scheduled by kernel
  - Cheaper than process
  - More expensive than user thread

Kernel Thread



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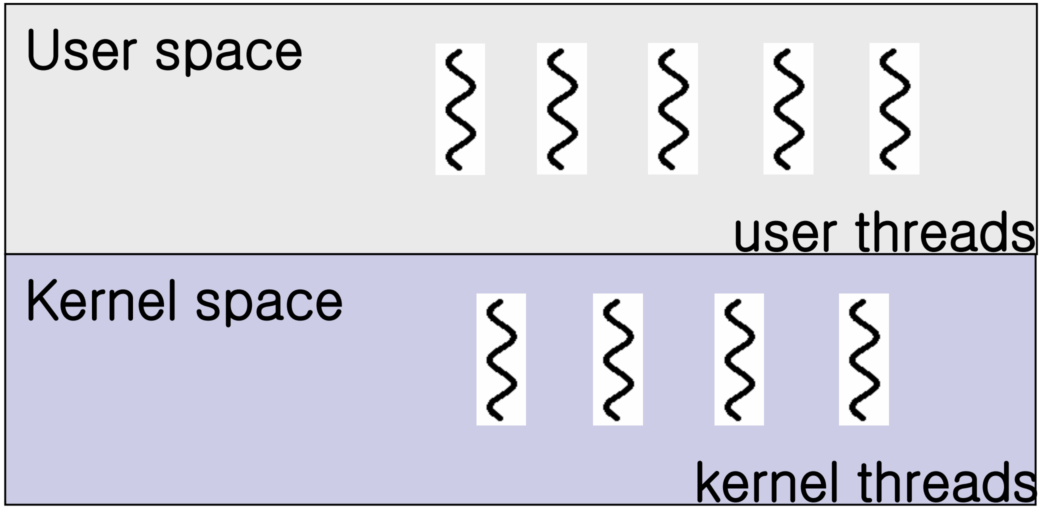
Multithreading Models

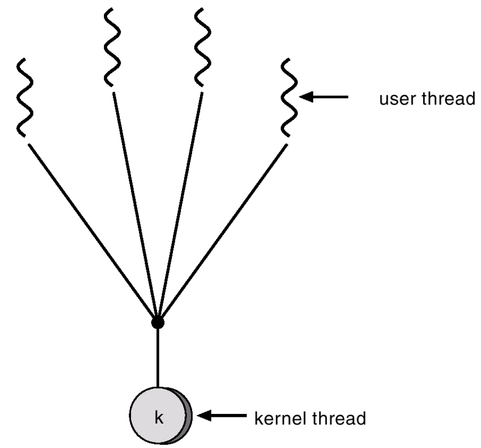
- Major issue: correspondence between user treads and kernel threads



Multithreading Models

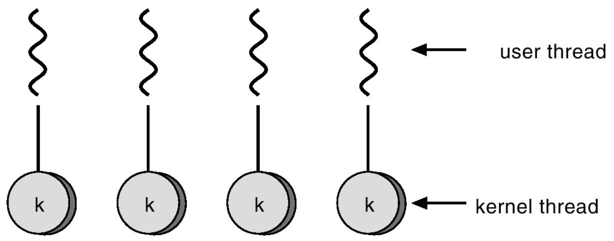
- Many-to-one model
  - Many user threads are mapped to single kernel thread
  - Threads are managed by user-level thread library

  Ex) Green threads, GNU Portable Threads



- One-to-one model
  - Each user thread is mapped to a kernel thread
  - Provides more concurrency
  - Problem: overhead

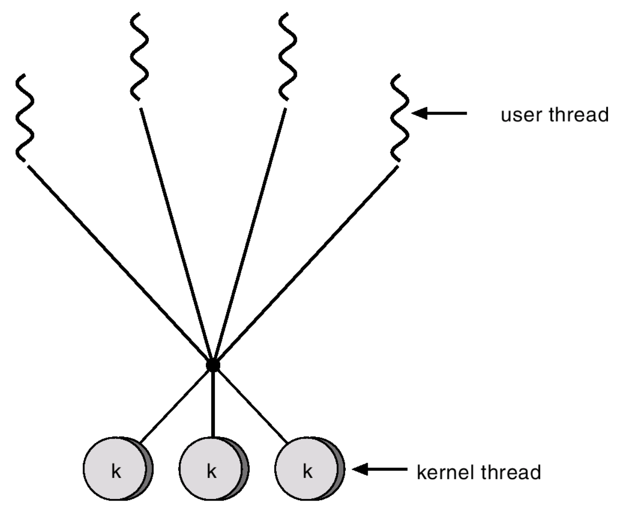
  Ex) Linux, Windows, Solaris

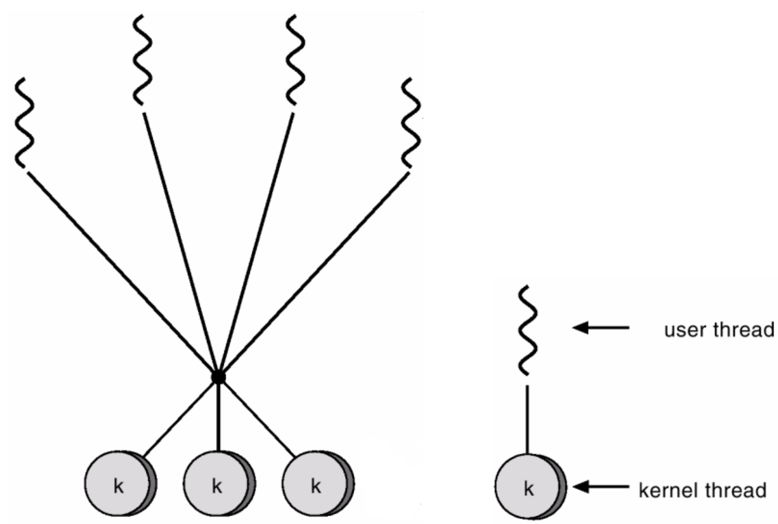


Multithreading Models

- Many-to-Many model
  - Multiplex many user level threads to smaller or equal number of kernel threads
  - Compromise between n:1 model and 1:1 model
- Two-level model
  - Variation of N:M model
  - Basically N:M model
  - A user thread can be bound to a kernel thread

  Ex) IRIX, HP-UX, Tru64, Solaris (old)



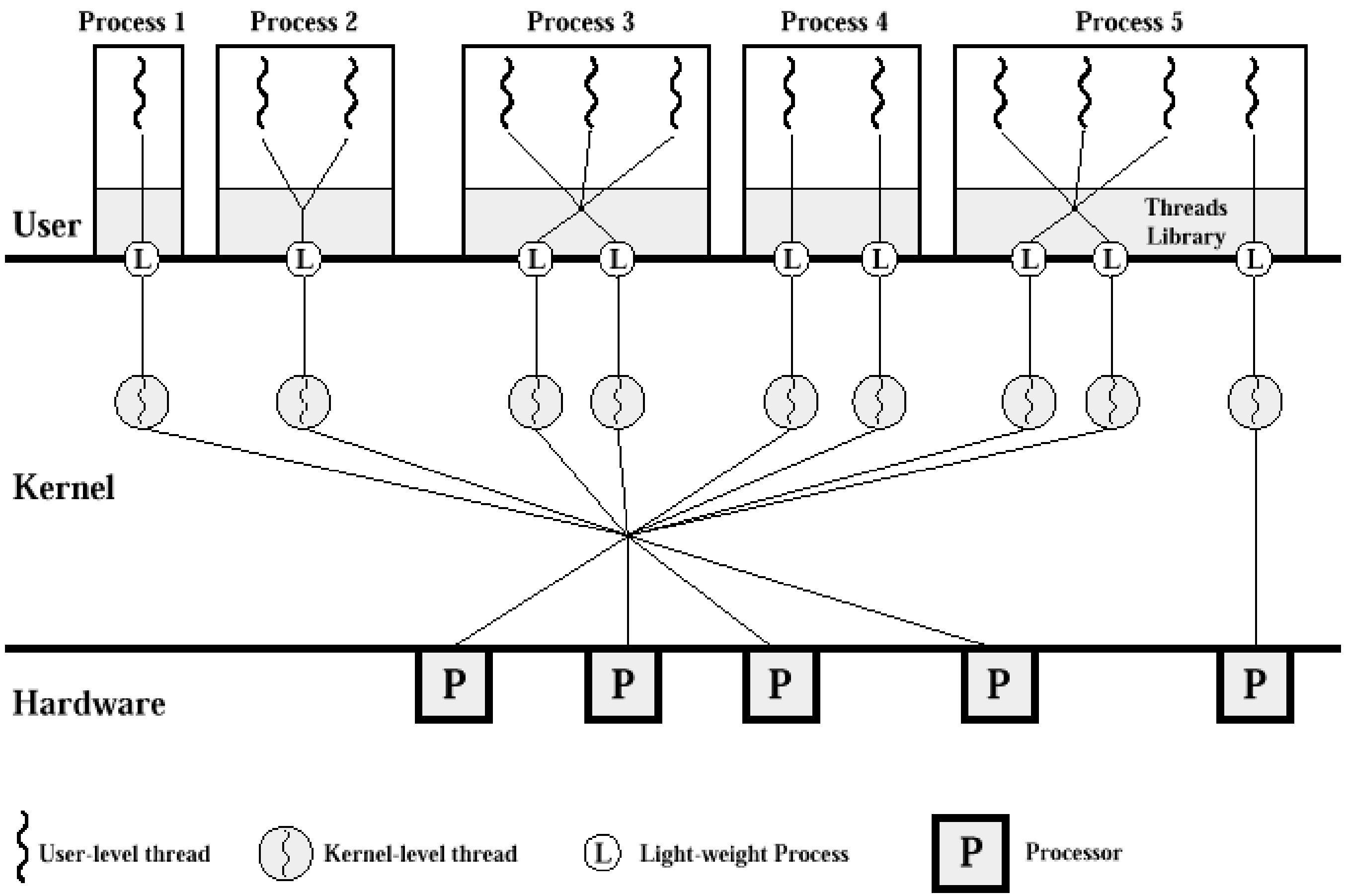


Scheduler Activation

- An issue about many-to-many model and two-level model: communication between the kernel and the thread library.
- Scheduler activation: one scheme for communication between user thread library and kernel
- In many-to-many model and two-level model, user threads are connected with kernel threads through LWP
- Lightweight process (LWP)
  - A data structure connecting user thread to kernel thread.
  - Basically, a LWP corresponds to a kernel thread, but there are some exceptions.
  - To the user-level thread library, a LWP appears to be a virtual processor.

Scheduler Activation and LWP

- Connection between user / kernel threads through LWP



Scheduler Activation

- Scheduler activation
  - Kernel provides a set of virtual processors(LWP's).
  - User level thread library schedules user threads onto virtual processors.
  - If a kernel thread is blocked or unblocked, kernel notices it to thread library(upcall).
  - Upcall handler schedules properly.
    - If a kernel thread is blocked, assign the LWP to another thread
    - If a kernel thread is unblocked, assign an LWP to it.

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Thread Libraries

- Thread library: set of API's to create and manage threads
  - User level library
  - Kernel level library

Examples)

  - POSIX Pthreads: a specification with various implementations.
    - LinuxThreads
    - NPTL (Native POSIX Thread Library)
    - GNU Portable Threads
    - Open source Pthreads for win32
    - Etc.
  - Win32 threads
  - Java threads

POSIX Pthreads

- Reading assignment: Search the Internet for the following functions, and study them.

- API functions
  - int pthread_create(pthread_t *thread, const pthread_attr_t *attr, void * (*start_routine)(void *), void *arg);
    - Creates thread
  - int pthread_attr_init(pthread_attr_t *attr);
    - Initializes *attr* by default values
  - int pthread_join(pthread_t th, void **thread_return);
    - Waits for a thread *th*.
  - void pthread_exit(void *retval);
    - Terminates thread

Example

```c
#include <pthread.h>
#include <stdio.h>

int sum; /* this data is shared by the thread(s) */
void *runner(void *param); /* the thread */

int main (int argc, char *argv[])
{
    pthread_t tid; /* the thread identifier */
    pthread_attr_t attr; /* set of thread attributes */
    if (argc < 2 ) {
        fprintf(stderr,"usage: a.out <integer>\n");
        exit(0);
    }
    if (atoi(argv[1]) < 0) {
        fprintf(stderr,"%d must be <= 0\n",atoi(argv[1]));
        exit(0);
    }
    /* get the default attributes */
    pthread_attr_init(&attr);
    /* create the thread */
    pthread_create(&tid,&attr,runner,argv[1]);
    /* now wait for the thread to exit */
    pthread_join(tid,NULL);
    printf("sum  = %d\n",sum);
    return 0;
}

/* The thread will begin control in this function */
void *runner(void *param)
{
    int upper = atoi (param);
    int i;
    sum = 0;
    if (upper > 0) {
        for (i = 1; i <= upper ; i++)
            sum += i;
    }
    pthread_exit(0);    // or return NULL;
}
```

Win32 Threads

- Create
```
HANDLE WINAPI CreateThread(
        LPSECURITY_ATTRIBUTES lpThreadAttributes,
        SIZE_T dwStackSize,
        LPTHREAD_START_ROUTINE lpStartAddress,
        LPVOID lpParameter,
        DWORD dwCreationFlags,
        LPDWORD lpThreadId
);
```
  See http://msdn.microsoft.com/library/default.asp?url=/library/en-us/dllproc/base/createthread.asp

- Wait
```
DWORD WINAPI WaitForSingleObject(
        HANDLE hHandle,
        DWORD dwMilliseconds
);
```

- Close (deallocate) handle
```
BOOL CloseHandle(LPDWORD lpThreadId);
```

Windows Multithreaded C Program

```
#include <windows.h>
#include <stdio.h>
DWORD Sum; /* data is shared by the thread(s) */

/* the thread runs in this separate function */
DWORD WINAPI Summation(LPVOID Param)
{
   DWORD Upper = *(DWORD*)Param;
   for (DWORD i = 0; i <= Upper; i++)
      Sum += i;
   return 0;
}

int main(int argc, char *argv[])
{
   DWORD ThreadId;
   HANDLE ThreadHandle;
   int Param;

   if (argc != 2) {
      fprintf(stderr,"An integer parameter is required\n");
      return -1;
   }
   Param = atoi(argv[1]);
   if (Param < 0) {
      fprintf(stderr,"An integer >= 0 is required\n");
      return -1;
   }

  /* create the thread */
  ThreadHandle = CreateThread(
     NULL, /* default security attributes */
     0, /* default stack size */
     Summation, /* thread function */
     &Param, /* parameter to thread function */
     0, /* default creation flags */
     &ThreadId); /* returns the thread identifier */

  if (ThreadHandle != NULL) {
     /* now wait for the thread to finish */
     WaitForSingleObject(ThreadHandle,INFINITE);

     /* close the thread handle */
     CloseHandle(ThreadHandle);

     printf("sum = %d\n",Sum);
  }
}
```

Java Threads

- Java threads are managed by the JVM
  - Typically, implemented using the threads model provided by underlying OS
- Java threads may be created by:
  - Extending Thread class
    - For detail, search 'Java Thread class' from Internet
  - Implementing the Runnable interface

```
public interface Runnable
{
    public abstract void run();
}
```

Java Thread using Thread Class

- Extending Thread class

```
class PrimeThread extends Thread {
    long minPrime;
    PrimeThread(long minPrime) {
        this.minPrime = minPrime;
    }

    public void run() {
        // compute primes larger than minPrime
         . . .
    }
}
```

- Launching thread

```
PrimeThread p = new PrimeThread(143);
p.start();
```

Java Thread using Running Interface

- Extending Thread class

```
class PrimeRun implements Runnable {
    long minPrime;
    PrimeRun(long minPrime) {
        this.minPrime = minPrime;
    }

    public void run() {
        // compute primes larger than minPrime
         . . .
    }
}
```

- Launching thread

```
PrimeRun p = new PrimeRun(143);
new Thread(p).start();
```

Java Multithreaded Program

```
class Sum
{
   private int sum;

   public int getSum() {
    return sum;
   }

   public void setSum(int sum) {
    this.sum = sum;
   }
}

class Summation implements Runnable
{
   private int upper;
   private Sum sumValue;

   public Summation(int upper, Sum sumValue) {
    this.upper = upper;
    this.sumValue = sumValue;
   }

   public void run() {
    int sum = 0;
    for (int i = 0; i <= upper; i++)
       sum += i;
    sumValue.setSum(sum);
   }
}
```

Java Multithreaded Program (Cont.)

```
public class Driver
{
   public static void main(String[] args) {
     if (args.length > 0) {
       if (Integer.parseInt(args[0]) < 0)
         System.err.println(args[0] + " must be >= 0.");
       else {
         Sum sumObject = new Sum();
         int upper = Integer.parseInt(args[0]);
         Thread thrd = new Thread(new Summation(upper, sumObject));
         thrd.start();
         try {
           thrd.join();
           System.out.println
                   ("The sum of "+upper+" is "+sumObject.getSum());
         } catch (InterruptedException ie) { }
       }
     }
     else
       System.err.println("Usage: Summation <integer value>"); }
}
```

Implicit Threading

- Creation and management of threads done by compilers and run-time libraries rather than programmers
- Three methods explored
  - Thread Pools
  - OpenMP
  - Grand Central Dispatch
- Other methods include Microsoft Threading Building Blocks (TBB), java.util.concurrent package

Thread Pools

- Create a number of threads in a pool where they await work
- Advantages:
  - Usually slightly faster to service a request with an existing thread than create a new thread
  - Allows the number of threads in the application(s) to be bound to the size of the pool
  - Separating task to be performed from mechanics of creating task allows different strategies for running task
    - i.e. Tasks could be scheduled to run periodically
- Windows API supports thread pools:

```
DWORD WINAPI PoolFunction(AVOID Param) {
    /*
     * this function runs as a separate thread.
    */
}
```

OpenMP

- Provides support for parallel programming in shared-memory environments
  - Set of compiler directives and an API for C, C++, FORTRAN
  - Identifies parallel regions – blocks of code that can run in parallel

- Create as many threads as there are cores

```
#pragma omp parallel              // each runs the statement
    printf("Hello, World!₩n");
```

- Run for loop in parallel

```
#pragma omp parallel for          // unroll loop over cores
    for(i=0;i<N;i++) {
        c[i] = a[i] + b[i];
    }
```

Grand Central Dispatch

- Apple technology for Mac OS X and iOS operating systems
- Extensions to C, C++ languages, API, and run-time library
- Allows identification of parallel sections
- Manages most of the details of threading
- Block is in "^{ }" – ^{ printf("I am a block"); }
- Blocks placed in dispatch queue
  - Assigned to available thread in thread pool when removed from queue

Grand Central Dispatch

- Two types of dispatch queues:
  - serial – blocks removed in FIFO order, queue is per process, called main queue
    - Programmers can create additional serial queues within program
  - concurrent – removed in FIFO order but several may be removed at a time
    - Three system wide queues with priorities low, default, high

```
dispatch_queue_t queue = dispatch_get_global_queue
   (DISPATCH_QUEUE_PRIORITY_DEFAULT, 0);

dispatch_async(queue, ^{ printf("I am a block."); });
```

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Threading Issues

- fork() and exec()
- Cancellation
- Signal handling
- Thread-local storage
- Scheduler activation (already covered)

fork() and exec()

- fork() on multithreaded process
  - Duplicates all threads in the process?
  - Duplicates only corresponding thread?
  - → UNIX supports two versions of fork
    - fork(), fork1()

- exec() on multithreaded process
  - Replace entire process

Cancellation

- Thread cancellation
  - Terminating a thread (target thread) before it has completed

```
pthread_t tid;

/* create the thread */
pthread_create(&tid, 0, worker, NULL);

. . .

/* cancel the thread */
pthread_cancel(tid);
```

- Problem with thread cancellation
  - A thread share the resource with other threads

  cf. A process has its own resource.

  → A thread can be cancelled while it updates data shared with other threads

Cancellation

- Cancellation scenarios
  - Asynchronous cancellation
    - Immediate termination
  - Deferred cancellation
    - Target thread checks periodically whether it should terminate.
      Ex) pthread_testcancel() of pthread
    - Safer than asynchronous cancellation

Thread Cancellation (Cont.)

- Invoking thread cancellation requests cancellation, but actual cancellation depends on thread state

Mode	State	Type
Off	Disabled	–
Deferred	Enabled	Deferred
Asynchronous	Enabled	Asynchronous

- If thread has cancellation disabled, cancellation remains pending until thread enables it
- Default type is deferred
  - Cancellation only occurs when thread reaches cancellation point
    - i.e. pthread_testcancel()
    - Then cleanup handler is invoked
- On Linux systems, thread cancellation is handled through signals

Signal Handling

- Signal: mechanism provided by UNIX to notify a process a particular event has occurred
  - A signal can be generated by various sources.
  - The signal is delivered to a process.
  - The process handles it.
    - Default signal handler (kernel)
    - User-defined signal handler

- Types of signal
  - Synchronous: signal from same process

    Ex) illegal memory access, division by 0
  - Asynchronous: signal from external sources

    Ex) <Ctrl>-C

What is a Signal?

- A signal is a software interrupt delivered to a process.
  - The operating system uses signals to report exceptional situations to an executing program
- A signal is a limited form of inter-process communication used in Unix and other POSIX-compliant operating systems.
  - Essentially it is an asynchronous notification sent to a process in order to notify it of an event that occurred

Examples of UNIX Signals

- Signals in UNIX (in signal.h)

```
#define SIGHUP      1  /* hangup */
#define SIGINT      2  /* interrupt */
#define SIGQUIT     3  /* quit */
#define SIGILL      4  /* illegal instruction (not reset when caught) */
#define SIGTRAP     5  /* trace trap (not reset when caught) */
#define SIGIOT      6  /* IOT instruction */
#define SIGABRT     6  /* used by abort, replace SIGIOT in the future */
#define SIGEMT      7  /* EMT instruction */
#define SIGFPE      8  /* floating point exception */
#define SIGKILL     9  /* kill (cannot be caught or ignored) */
#define SIGBUS      10 /* bus error */
#define SIGSEGV     11 /* segmentation violation */
#define SIGSYS      12 /* bad argument to system call */
#define SIGPIPE     13 /* write on a pipe with no one to read it */
#define SIGALRM     14 /* alarm clock */
#define SIGTERM     15 /* software termination signal from kill */
```

Installing Signal Handler

- **Defining signal handler**

```
typedef void (*sighandler_t)(int);
sighandler_t signal(int signum,
                    sighandler_t handler);
```

- **Example**

```
#include <signal.h>
#include <unistd.h>

void sig_handler(int signo);

// press CTRL-₩ to terminate this program
int main()
{
    int i = 0;
    signal(SIGINT, (void *)sig_handler);

    while(1){
        printf("%d₩n", i++);
        sleep(1);
    }
    return 1;
}

void sig_handler(int signo)
{
    printf("SIGINT was received!₩n");
}
```

Signal Handling

- Question: To what thread the signal should be delivered?

- Possible options
  - To the thread to which the signal applies
  - To every thread in the process
  - To certain threads in the process
  - Assign a specific thread to receive all signals

  ➔ depend on type of signal

- Another scheme: specify a thread to deliver the signal

  Ex) pthread_kill(tid, signal) in POSIX

Thread-Local Storage

- Thread-local storage (TLS) allows each thread to have its own copy of data
- Useful when you do not have control over the thread creation process (i.e., when using a thread pool)
- Different from local variables
  - Local variables visible only during single function invocation
  - TLS visible across function invocations
- Similar to static data
  - TLS is unique to each thread

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Windows XP Threads

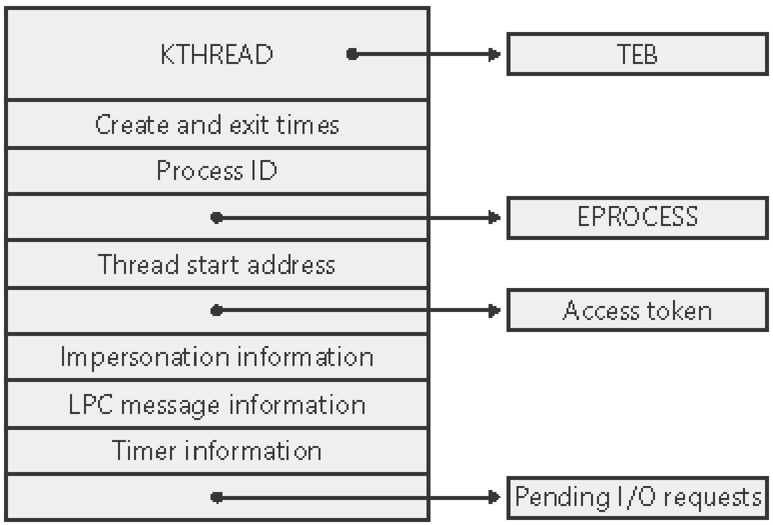
- Implements the one-to-one mapping, kernel-level
  - Additionally, many-to-many model is supported by fiber library
- Each thread contains
  - A thread id, register set, separate user and kernel stacks, private data storage area (for run-time libraries and DLLs)

  Cf. The register set, stacks, and private storage area are known as the context of the thread.

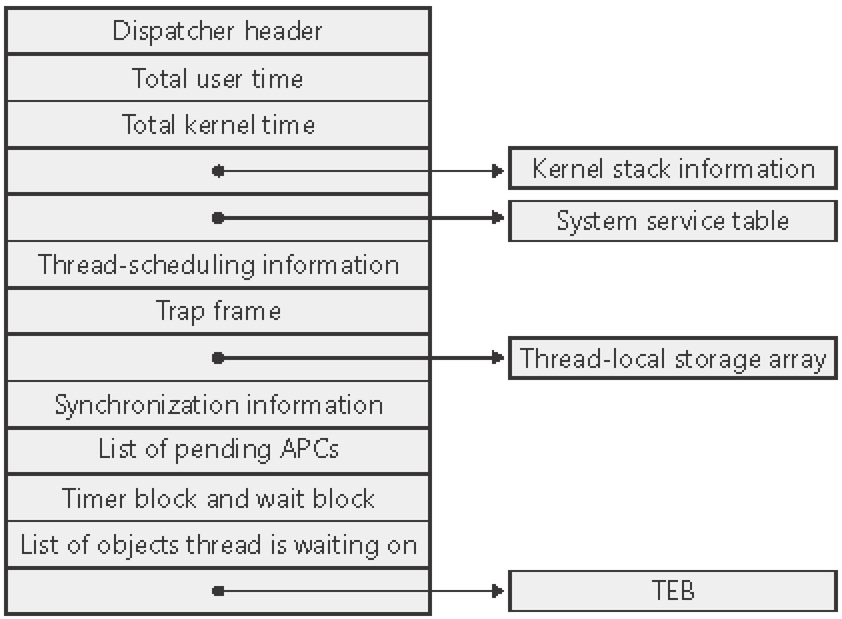
Internal Data Structures

- The primary data structures of a thread include:
  - ETHREAD (executive thread block)
  - KTHREAD (kernel thread block)
    - Information for thread scheduling and synchronization
  - TEB (thread environment block)
    - Context information for the image loader and various Windows DLL

Layout of ETHREAD and KTHREAD

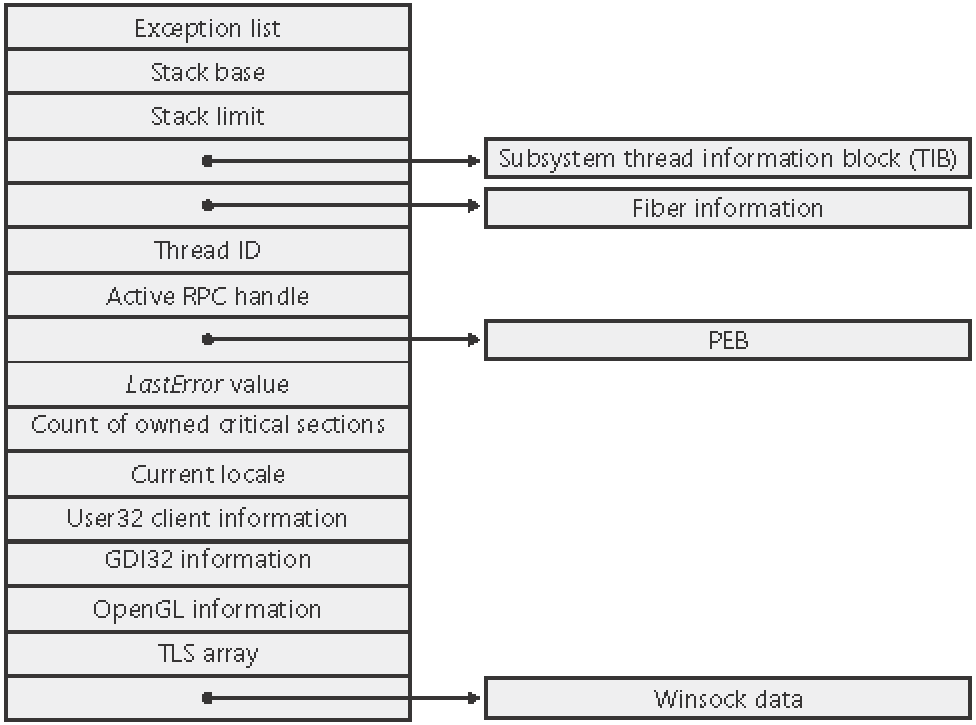


ETHREAD

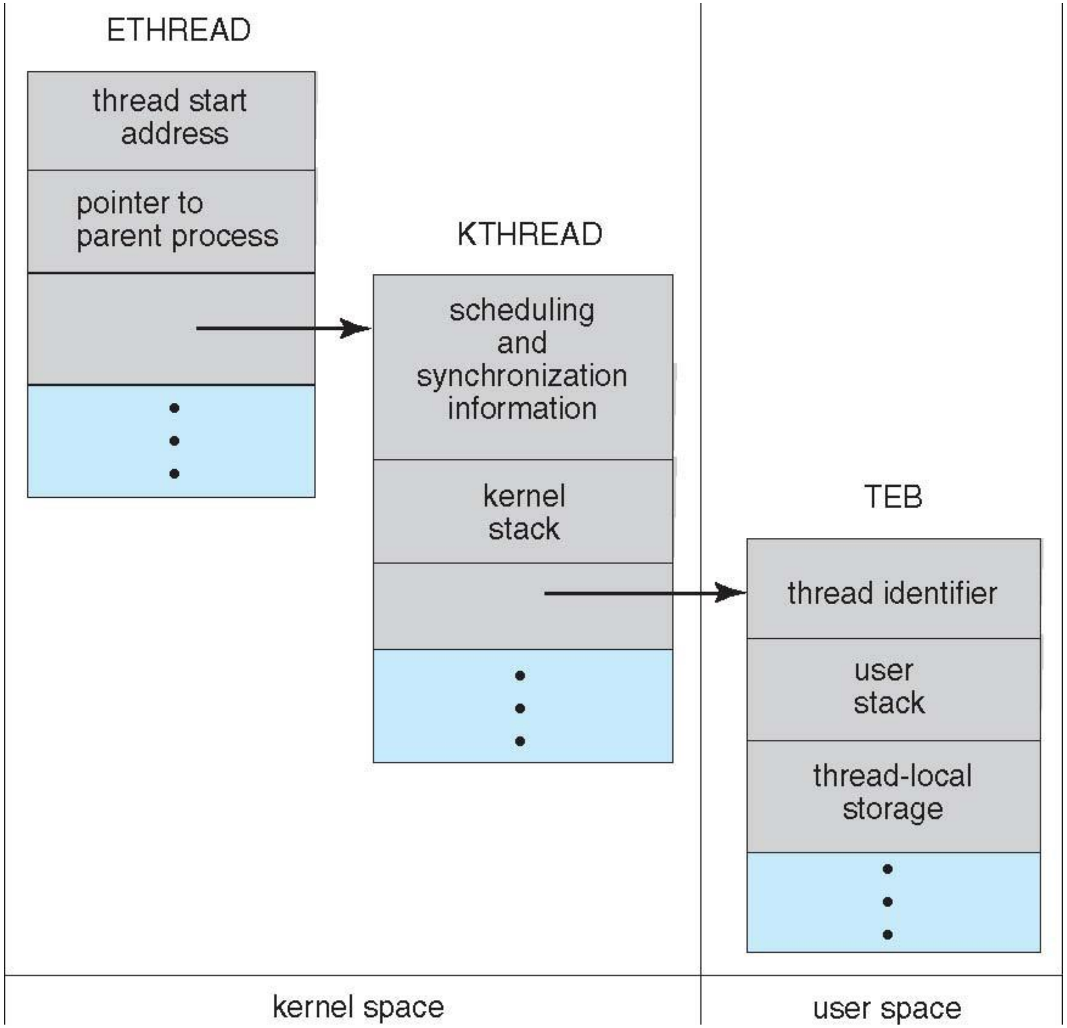


KTHREAD

Layout of TEB



Windows XP Threads



Linux Threads

- First implementation: LinuxThreads
  - Thread is created by clone() system call
  - However, no difference between process and thread
    - Term '**task**' is used more frequently than 'process' or 'thread'
  - User can control how much the resource is shared between parent and child.

Linux Threads

- Problems of *LinuxThreads*
  - It did not scale well,
    - There is a limitation on the number of threads, generally between 1024 and 8192.
    - The overhead of creating and destroying processes is relatively high.
  - The manager thread resulted in some fragility and another scaling bottleneck.
  - Some required POSIX semantics were not possible. Each thread had its own PID.
- NPTL (Native POSIX Thread Library)
  - Better than LinuxThreads in performance and compatibility