Chapter 4: Threads – Outline

- What are threads ? How do they compare with processes ?
- Why are threads important ?
- What are the common multithreading models ?
- What are the common multithreading libraries ?
- Discussion on threading issues.
- Examples of threads in contemporary OSes.

Process Overview

- The basic unit of CPU scheduling is a process.
- To run a program (a sequence of instructions), create a process.
- Process properties
  - `fork()` → `exec()` can be used to start new program execution
  - processes are well protected from each other
  - context-switching between processes is fairly expensive
  - inter-process communication used for information sharing and co-ordination between processes
    - shared memory
    - message passing

Is the Process Abstraction Always Suitable?

- Consider characteristics for a game software
  - different code sequences for different game objects
    - soldiers, cities, airplanes, cannons, user-controlled heroes, etc.
  - each object is more or less independent
- Problems
  - single monolithic process may not utilize resources optimally
    - can create a process for each object
  - action of an object depends on game state
    - sharing and co-ordination of information necessary
    - IPC can be expensive
  - number of objects proceed simultaneously
    - may involve lots of context switches
    - process context switches are expensive

Is the Process Abstraction Always Suitable? (2)

- Need ability to run multiple sequences of code (threads of control) for different object
  - individual process only offers one thread of control
- Need a way for threads of control to share data effectively
  - processes NOT designed to do this
- Protection between threads of control not very important
  - all in one application, anyway !
  - process is an over-kill
- Switching between threads of control must be efficient
  - context switching involves a lot of overhead
- Different threads of control may share most information
  - processes duplicate entire address space

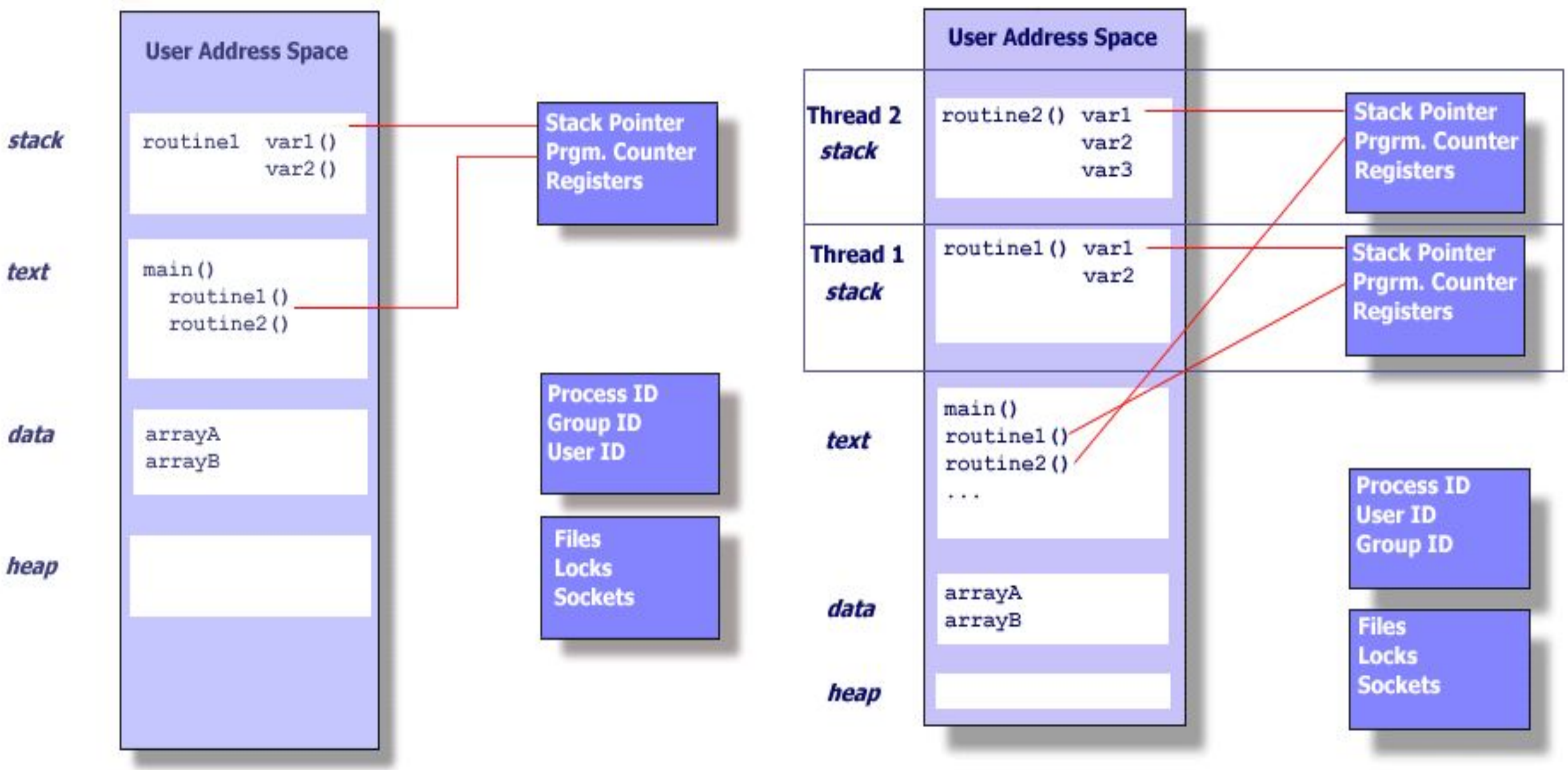
Threads to the Rescue

- *Threads* are designed to achieve all the above requirements !
  - do as little as possible to allow *concurrent* execution of a thread of control
- Thread is known as a *lightweight* process
  - only the necessary context information is re-generated
    - thread-context: PC, registers, stack, other misc. info
    - process-context: also includes data and code regions
  - threads are executed within a process
    - code and data shared among different threads
    - reduced communication overhead
  - smaller context
    - slightly faster context switching
  - a single address space for all threads in a process
    - reduced inter-thread protection

Thread Basics

- Thread – *a lightweight process*
  - have their own independent flow of control
  - share process resources with other sibling threads
  - exist within the context space of the same process
- Threads shared data
  - process instructions
  - most data
  - open files (descriptors)
  - signals and signal handlers
  - current working directory
  - user and group id
- Threads specific data
  - thread id
  - registers, stack pointer
  - thread-specific data
  - stack (for activation records)
  - signal mask
  - scheduling properties
  - return value

Single and Multithreaded Process



source: https://computing.llnl.gov/tutorials/pthreads/

Thread Benefits

- Responsiveness
  - for an interactive user, if part of the application is blocked
- Resource Sharing
  - easier, via memory sharing
  - be aware of synchronization issues
- Economy
  - sharing reduces creation, context-switching, and space overhead
- Scalability
  - can exploit computational resources of a multicore CPU

Thread Programming In Linux

- Threads can be created using the *Pthreads* library
  - IEEE POSIX C language thread programming interface
  - may be provided either as user-level or kernel-level

- Pthreads API
  - *Thread management* – functions to create, destroy, detach, join, set/query thread attributes
  - *Mutexes* – functions to enforce synchronization. Create, destroy, lock, unlock mutexes
  - *Condition variables* – functions to manage thread communication. Create, destroy, wait and signal based on specified variable values

Pthreads Example

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

int sum; /* data shared by all threads */
void runner(void param); /* thread function prototype */

int main (int argc, char *argv[])
{
    pthread_t tid; /* thread identifier */
    pthread_attr_t attr /* set of thread attributes */

    if(atoi(argv[1]) < 0) {
        fprintf(stderr, "%d must be >=0\n", atoi(argv[1]));
        return -1;
    }
    /* get the default thread attributes */
    pthread_attr_init(&attr);
    /* create the thread */
    pthread_create(&tid, &attr, runner, argv[1]);
    /* wait for the thread to exit */
    pthread_join(tid, NULL);
    fprintf(stdout, "sum = %d\n", sum);
}
```

Pthreads Example (2)

```
.... (cont. from previous page...)

/* The thread will begin control in this function */
void *runner (void  *param)
{
    int i, upper = atoi(param);
    sum = 0;

    for(i=1 ; i<=upper ; i++)
        sum += i;

    pthread_exit(0);
}
```

Pthread Example – API Calls

- pthread_attr_init – initialize the thread attributes object
  - `int pthread_attr_init(pthread_attr_t *attr);`
  - defines the attributes of the thread created
- pthread_create – create a new thread
  - `int pthread_create(pthread_t *restrict thread, const pthread_attr_t *restrict attr, void *(*start_routine)(void*), void *restrict arg);`
  - upon success, a new thread id is returned in `thread`
- pthread_join – wait for thread to exit
  - `int pthread_join(pthread_t thread, void **value_ptr);`
  - calling process blocks until thread exits
- pthread_exit – terminate the calling thread
  - `void pthread_exit(void *value_ptr);`
  - make return value available to the joining thread

User Vs. Kernel Level Threads

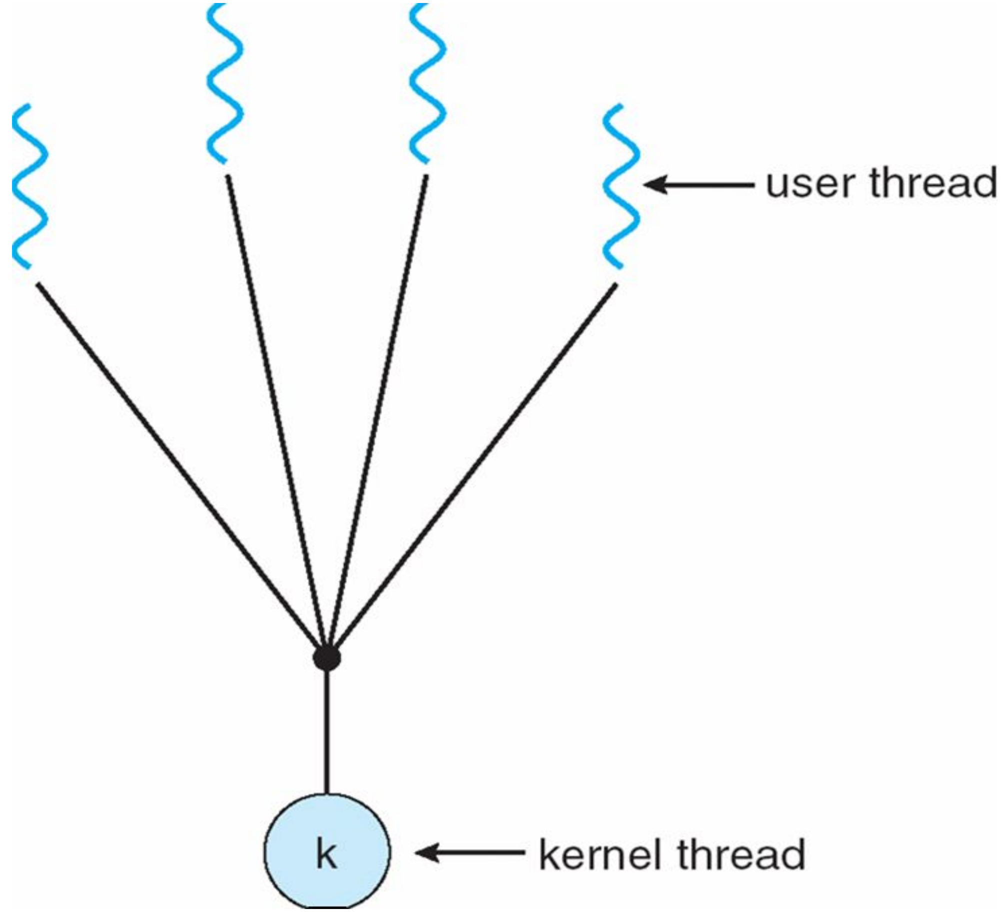
- User-level threads – manage threads in user code
  - advantages – efficient and flexible in space, speed, switching, and scheduling
  - disadvantages – one thread blocked on I/O can block all threads, difficult to automatically take advantage of SMP
  - examples of thread libraries – POSIX Pthreads, Windows threads, Java Threads, GNU portable Threads
- Kernel-level threads – kernel manages the threads
  - Advantages – removes disadvantages of user-level threads
  - Disadvantages – greater overhead due to kernel involvement
  - Examples – provided by almost all general-purpose OS
    - Windows, Solaris, Linux, Mac OS, etc.

Multithreading Models

- Relationships between user and kernel threads
  - Many-to-One
  - One-to-One
  - Many-to-Many

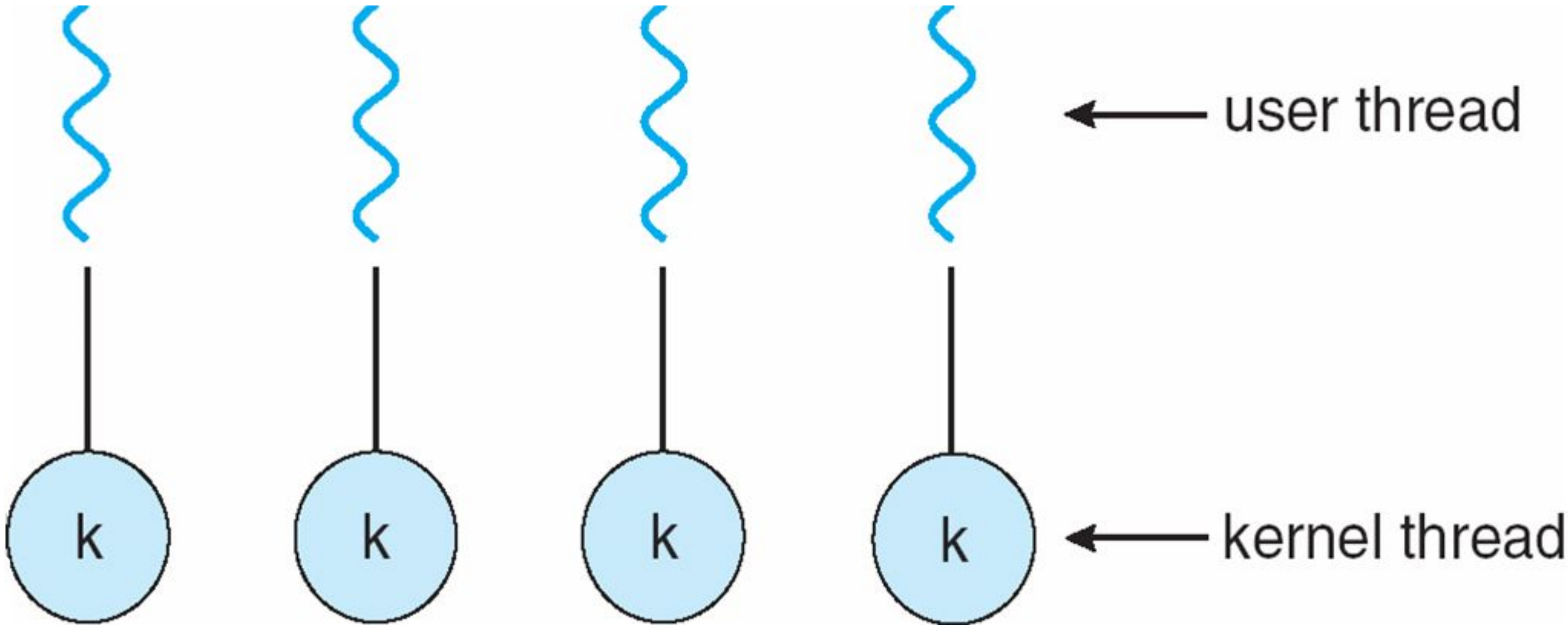
Many–to–One Multithreading Model

- Many user-level threads mapped to single kernel thread
  - examples – Solaris Green Threads, GNU Portable Threads



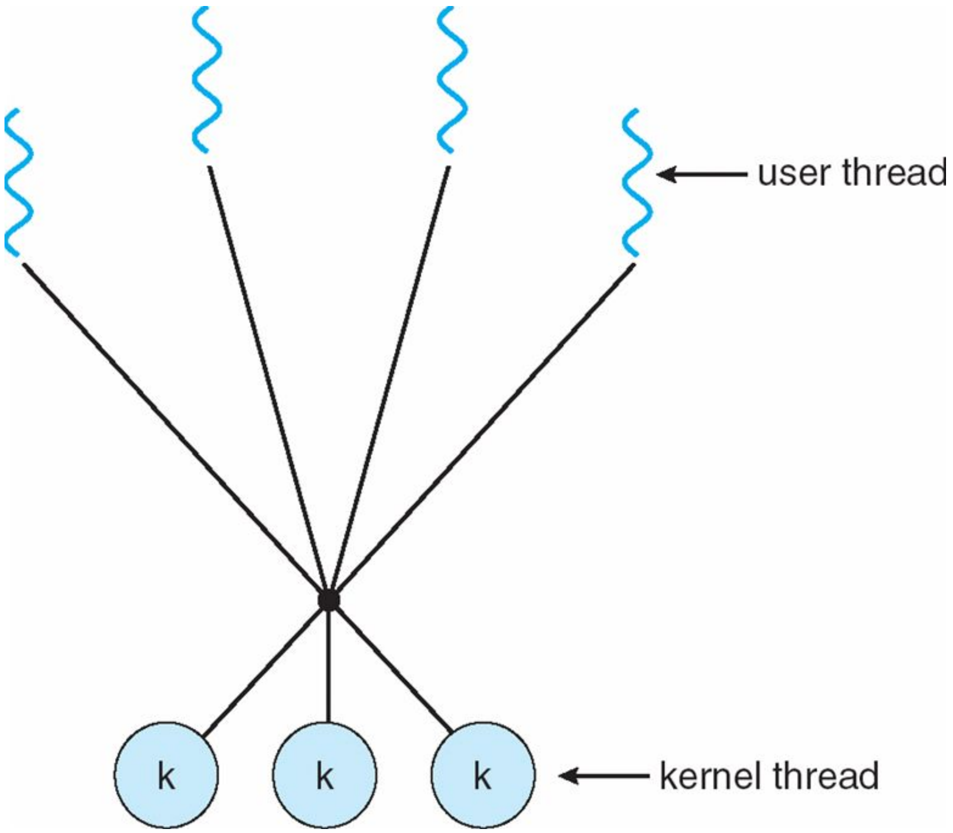
One–to–One Multithreading Model

- Each user-level thread maps to kernel thread
  - examples – Windows NT/XP/2000, Linux, Solaris 9 and later



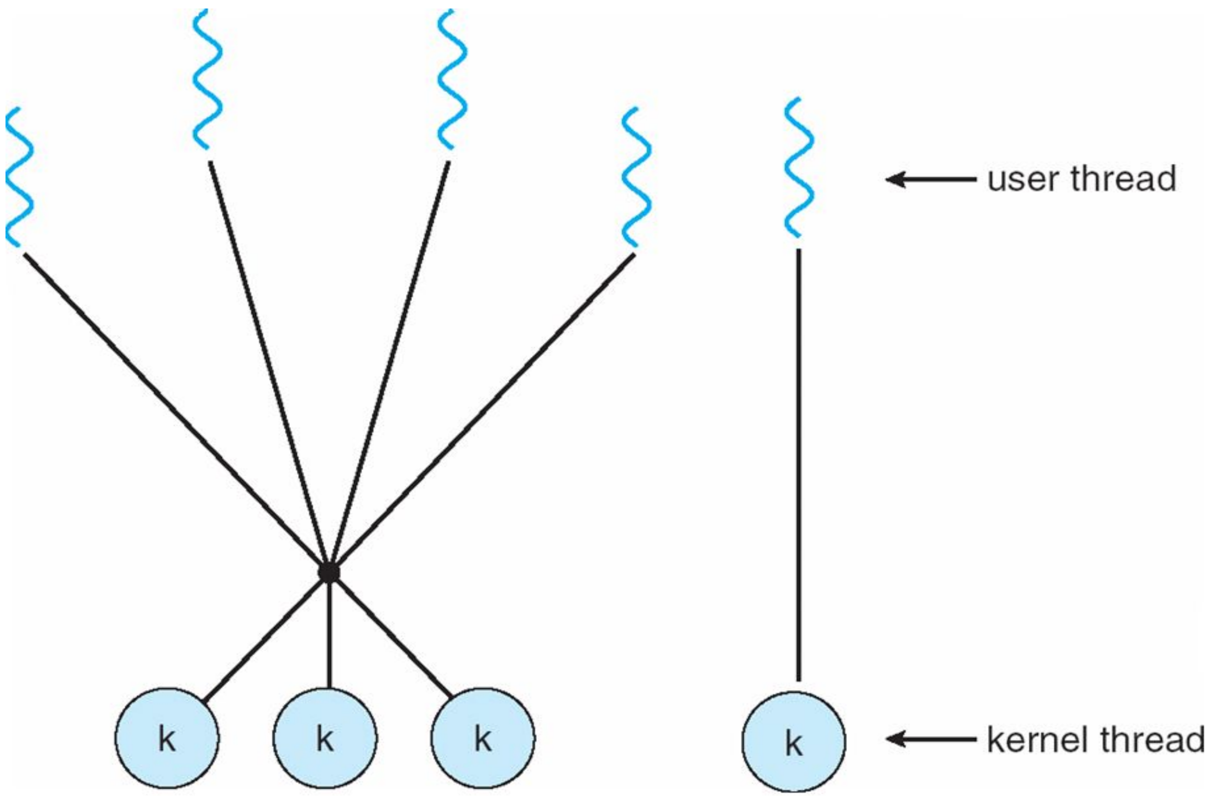
Many–to–Many Multithreading Model

- *m* user level threads mapped to *n* kernel threads
  - operating system can create a sufficient number of kernel threads
  - examples – Solaris prior to v9, Windows NT/2000 *ThreadFiber* package



Two-level Multithreading Model

- Similar to M:M, except that it also allows a user thread to be **bound** to kernel thread
  - examples – IRIX, HP-UX, Tru64 UNIX, Solaris 8 and earlier



Threading Issues

- Semantics of **fork()** and **exec()** system calls
- Thread cancellation of target thread
- Signal handling
- Implicit Threading
- Thread-specific data
- Scheduler activations

Semantics of fork() and exec()

- Does fork() duplicate only the calling thread or all threads ?
  - some systems provide two versions of fork()
  - Linux: only duplicate the thread calling fork()
- How about exec() ?
  - most systems maintain the semantics of exec()
  - Linux: complete process address space (all threads) are overwritten
- Observations
  - exec() called immediately after fork

    duplicating all threads is unnecessary

Thread Cancellation

- Terminating a thread before it has finished
- Asynchronous cancellation
  - terminates the target thread immediately
  - allocated resources may not all be freed easily
  - status of shared data may remain ill-defined
- Deferred cancellation
  - target thread terminates itself
  - orderly cancellation can be easily achieved
  - failure to check cancellation status may cause issues
- Linux supports both cancellation types
  - do: `man pthread_cancel`

Signal Handling

- Signals are used in UNIX systems to notify a process that a particular event has occurred
- A signal handler is used to process signals
  - OS may deliver the signal to the appropriate process
  - OS or process handles the signal
- Types of signals
  - synchronous – generated by some event in the process
  - asynchronous – generated by an event outside the process
- Where to deliver a signal in multithreaded programs ?
  - deliver the signal to the thread to which the signal applies
  - deliver the signal to every thread in the process
  - deliver the signal to certain threads in the process
  - assign a specific thread to receive all signals for the process

Implicit Threading

- Writing correct multi-threaded programs
  - can cause latency and performance issues
  - is more difficult for programmers
- Use compilers and runtime libraries to create and manage threads (semi) automatically.
- Some example methods include
  - Thread pools
  - OpenMP
  - Grand central dispatch, MS Thread building blocks (TBB), java.util.concurrent package

Thread Pools

- Concerns with multithreaded applications
  - continuously creating and destroying threads is expensive
  - overshooting the bound on concurrently active threads
- Thread Pools
  - create a number of threads in a pool where they await work
  - number of threads can be proportional to the number of processors
- Advantages
  - faster to service a request with an existing thread than create a new thread every time
  - allows the number of threads in the application(s) to be bound to the size of the pool

OpenMP

- Compiler directives and an API for C, C++, FORTRAN
- Supports parallel programming in shared-memory environments
- *User* identifies parallel region
- Create as many threads as there are cores

```
#pragma omp parallel
```

- Run for loop in parallel

```
#pragma omp parallel for
for(i=0 ; i<N ; i++)
    c[i] = a[i] + b[i];
```

```
#include <omp.h>
#include <stdio.h>

int main(int argc, char *argv[])
{
  /* sequential code */

  #pragma omp parallel
  {
    printf("I am a parallel region.");
  }

  /* sequential code */

  return 0;
}
```

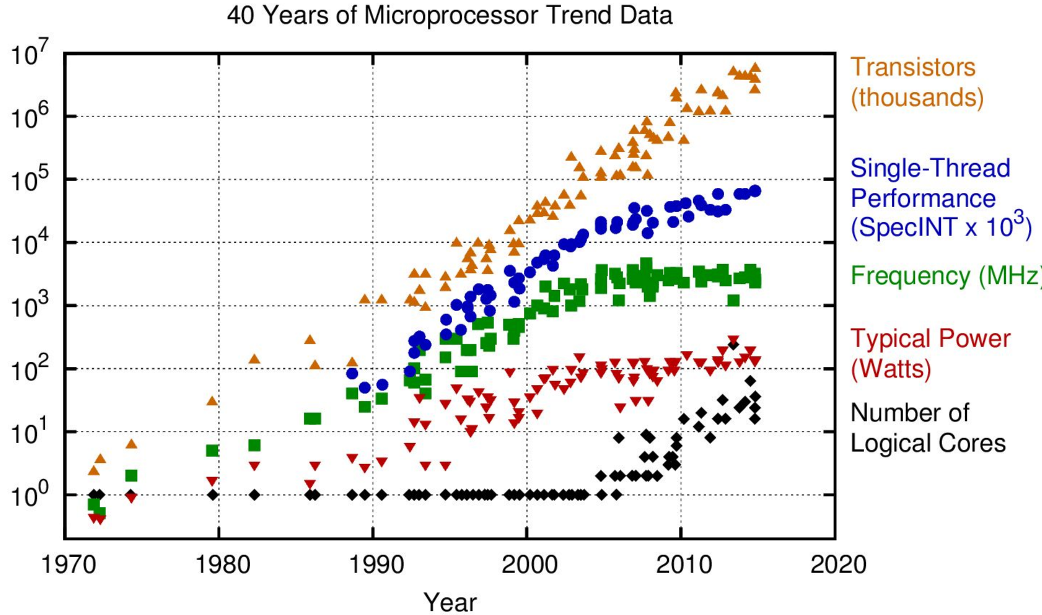
Linux Thread Implementation

- Linux refers to them as *tasks* rather than *threads*
- Thread creation is done through **clone()** system call
- **clone()** allows a child task to share the address space of the parent task (process)

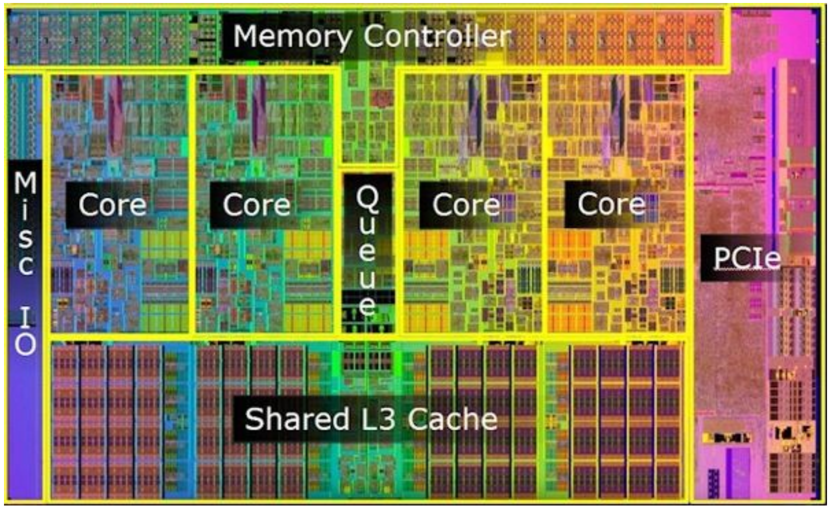
flag	meaning
CLONE_FS	File-system information is shared.
CLONE_VM	The same memory space is shared.
CLONE_SIGHAND	Signal handlers are shared.
CLONE_FILES	The set of open files is shared.

Multicore Processors

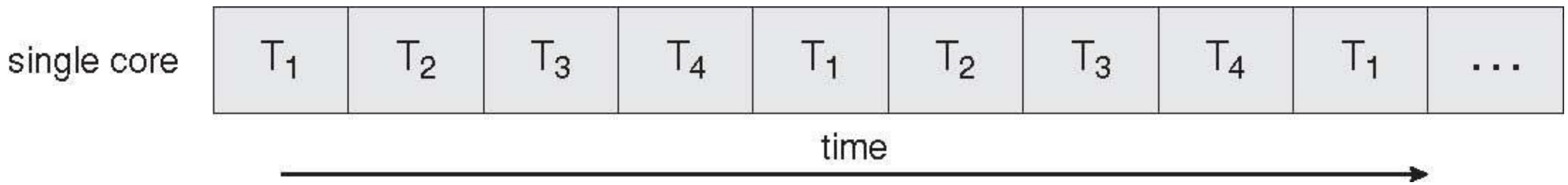
- Multiple processing cores on a single chip.
- Reasons for a shift to multicore processors
  - power wall
  - limits to frequency scaling
  - transistor scaling still a reality
- Multicore programming Vs. multicomputer programming
  - same-chip communication is faster
  - memory sharing is easier and faster



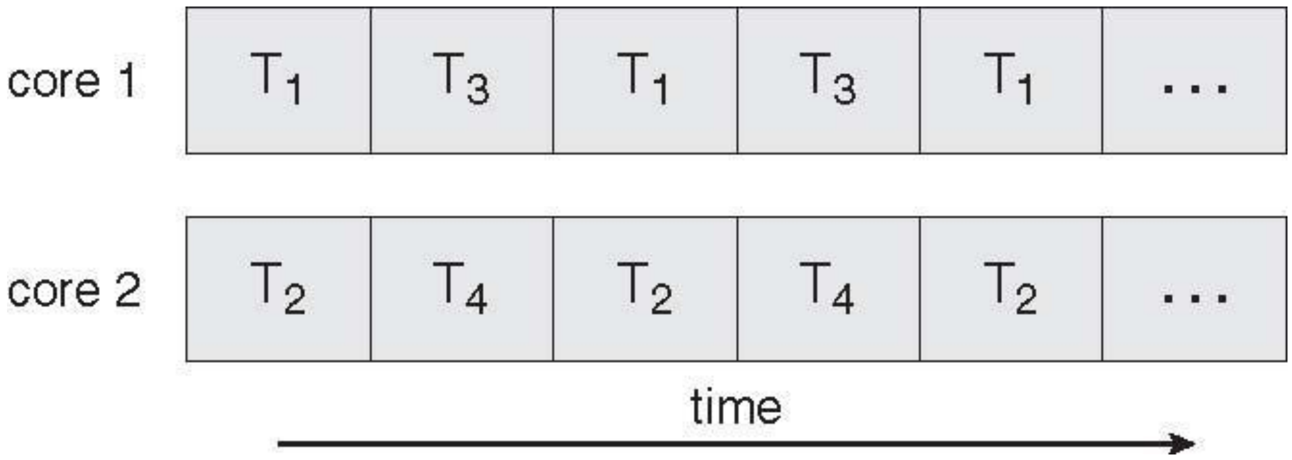
Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2015 by K. Rupp



Single Core Vs. Multicore Execution



Single core execution



Multiple core execution

Challenges for Multicore Programming

- Dividing activities for balanced workload
- Data splitting
- Data dependency between tasks running concurrently
- Testing and debugging issues