Threads and Concurrency

Operating Systems

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(with slides borrowed from Prof. Jerry Chou)

Outline

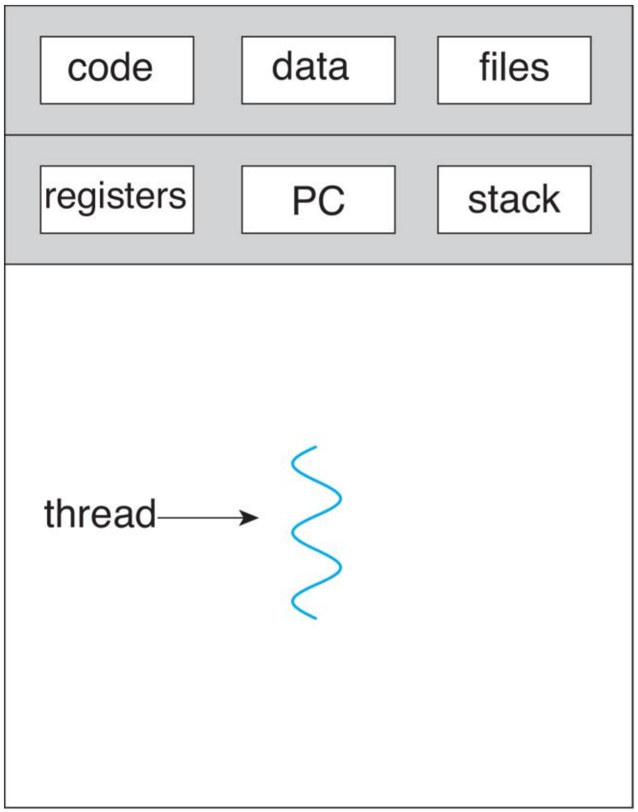
- Thread introduction
- Multi-threading models
- Threaded case study
- Threading issues

Thread Introduction

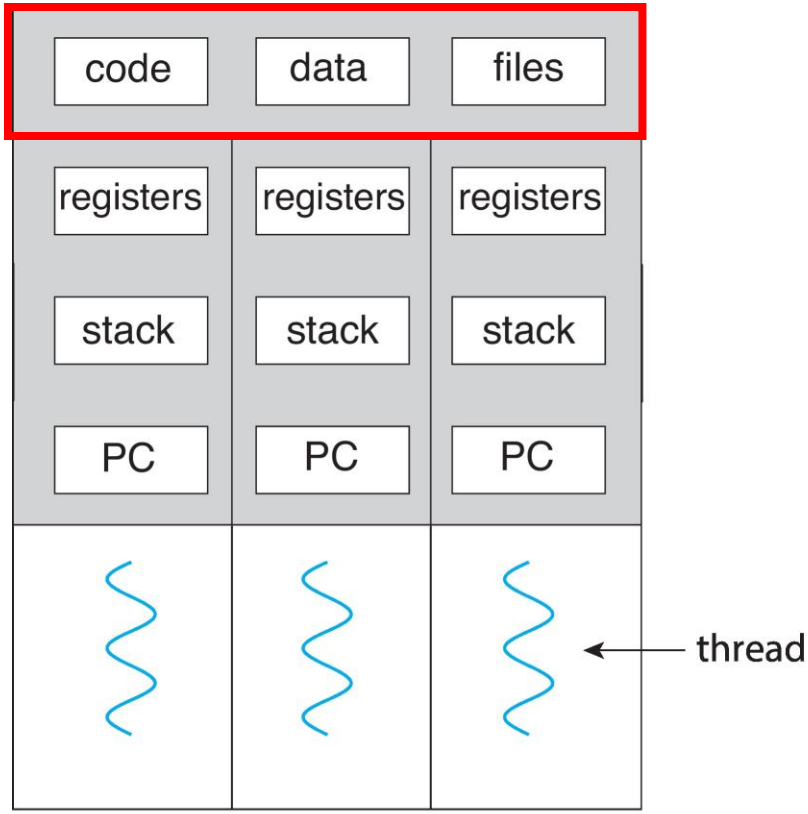
Threads

- A thread is a **lightweight** process
  - Basic unit of CPU utilization
- All threads belonging to the same process **share**
  - Code section
  - Data section (including dynamic allocated variables)
  - OS resources (e.g., open files)
- **But each thread has its own** (thread control block)
  - Thread ID
  - Program counter
  - Register set
  - Stack

Threads (cont.)



single-threaded process



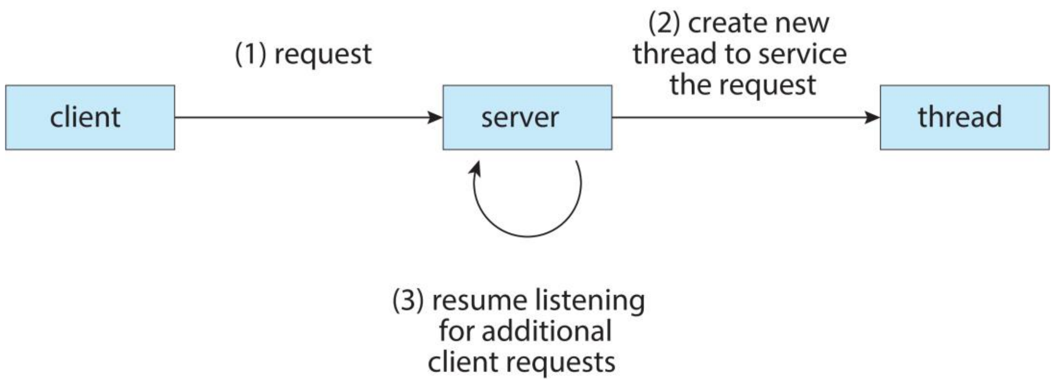
multithreaded process

Motivation

- Most modern applications are multi-threaded
- Threads run within an application, multiple tasks within an application can be implemented by separate threads
  - Update display
  - Fetch data
  - Spell checking
  - Answer a network request
- Thread creation is much cheaper than process creation
- Simplify code and increase efficiency
- Kernels are also generally multi-threaded

Motivation (cont.)

- Example:
  - **Web browser**
    - One thread displays contents while the other thread receives data from network
  - **Web server**
    - One request / process results in poor performance
    - One request / thread achieves better performance as code and resource sharing



  - **RPC server**
    - One RPC request / thread

Benefits of Threads

- **Responsiveness**
  - Allow continued running of a process even if part of it is blocked or is performing a lengthy operation
- **Resource sharing**
  - Thread share resources of process
- **Scalability**
  - Take advantage of multicore architectures
- **Economy**
  - Thread creation is cheaper than process creation
    - Ex: creating a thread is 30x cheaper than a process in Solaris
  - Thread switching has lower overhead than context switching

Benefits of Threads (cont.)

- Lower creation / management cost v.s. process

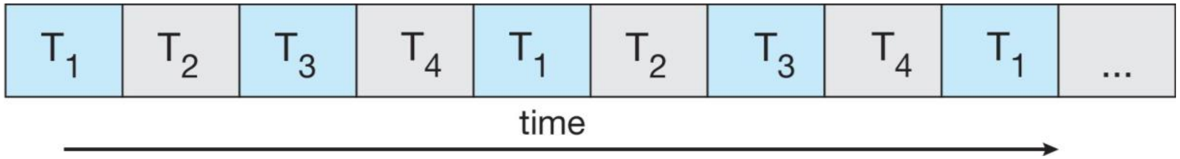
platform	fork()	pthread_create()	speedup
AMD 2.4 GHz Opteron	17.6	1.4	15.6x
IBM 1.5 GHz POWER4	104.5	2.1	49.8x
INTEL 2.4 GHz Xeon	54.9	1.6	34.3x
INTEL 1.4 GHz Itanium2	54.5	2.0	27.3x

- Faster inter-process communication v.s. MPI

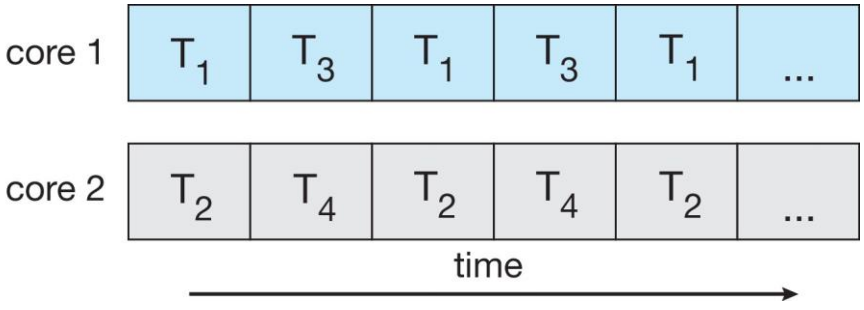
platform	MPI Shared Memory BW (GB/sec)	Pthreads Worst Case Memory-to-CPU BW (GB/sec)	speedup
AMD 2.4 GHz Opteron	1.2	5.3	4.4x
IBM 1.5 GHz POWER4	2.1	4	1.9x
INTEL 2.4 GHz Xeon	0.3	4.3	14.3x
INTEL 1.4 GHz Itanium2	1.8	6.4	3.6x

Multi-Core Programming

- **Concurrency**
  - Supports more than one task making progress
  - Single processor/core with scheduler can provide concurrency

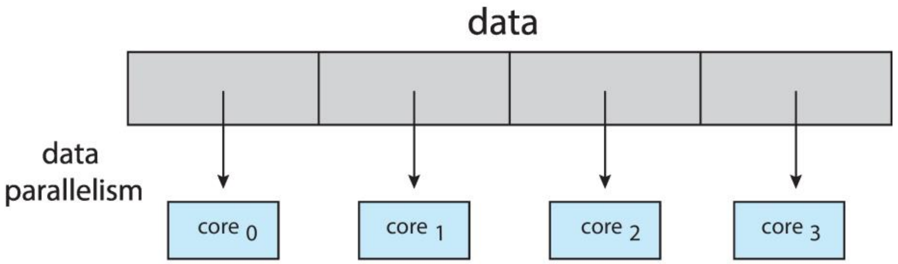


- **Parallelism**
  - A system can perform more than one task simultaneously

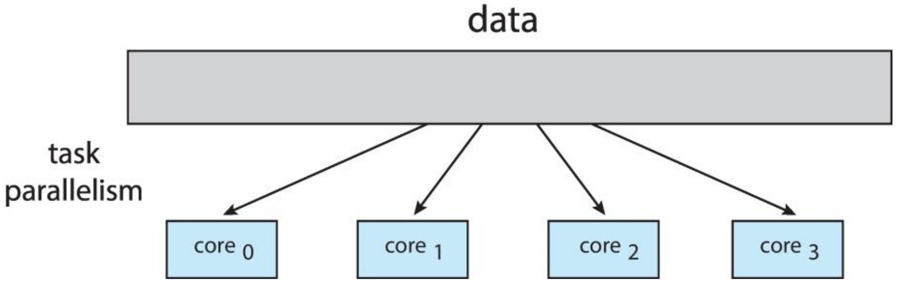


Parallelism

- **Data parallelism**
  - Distribute subsets of the same data across multiple cores
  - Same operation on each



- **Task parallelism**
  - Distribute threads across cores, each thread performing unique operation



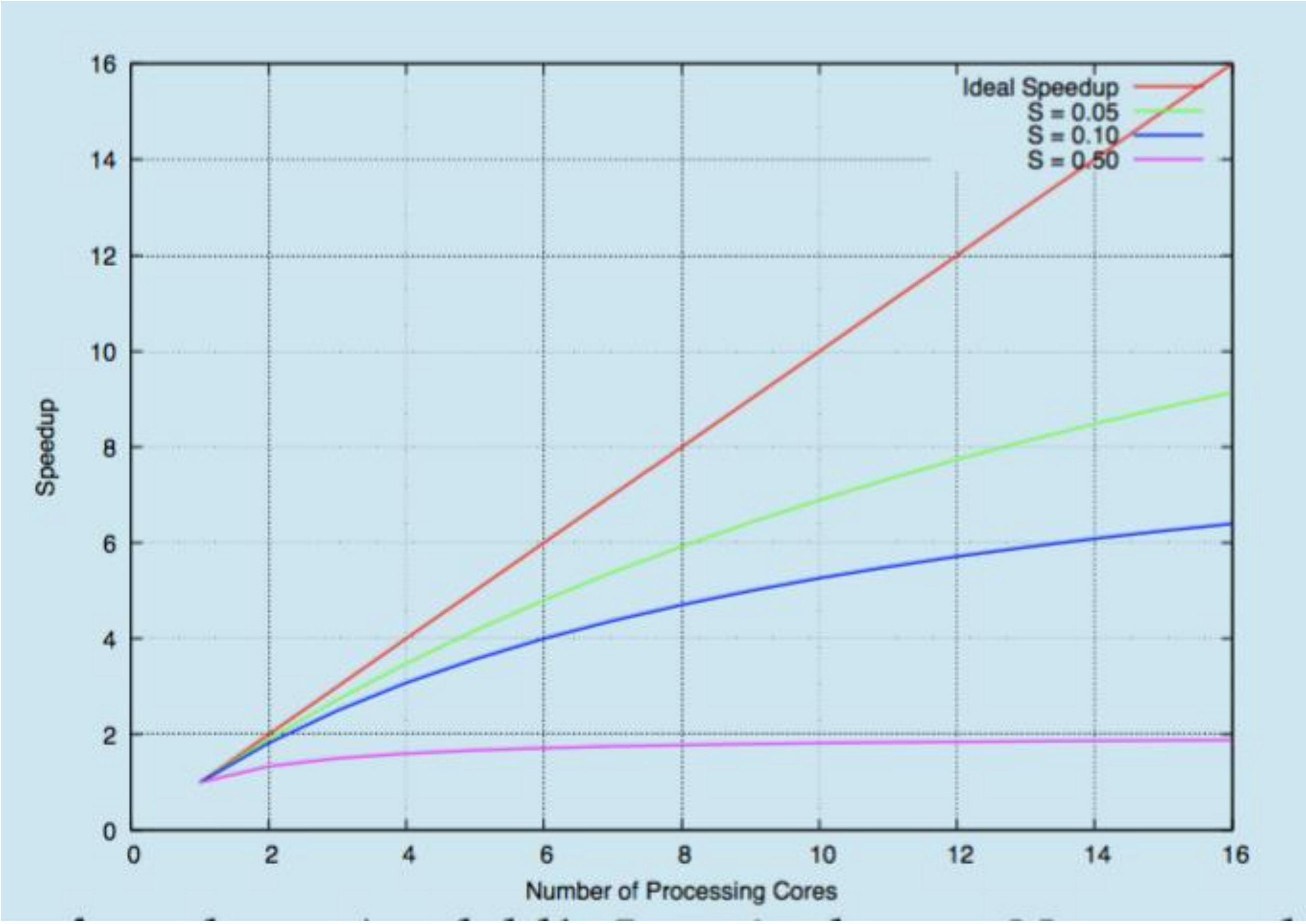
Amdahl's Law

- Identify performance gains from adding additional cores to an application that has both serial and parallel components
- Assume ***S*** is the serial portion and the system has ***N*** processing cores

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

  - Example: 75% parallel / 25% serial, moving from 1 to 2 cores results in a speedup of 1.6 times
  - As *N* approaches infinity, speedup approaches *1/S*

Amdahl’s Law (cont.)



Challenges in Multi-Core Programming

- **Dividing activities**
  - Divide program into concurrent tasks
- **Data splitting**
  - Divide data accessed and manipulated by the tasks
- **Data dependency**
  - Synchronize data access
- **Balance**
  - Evenly distribute tasks to cores
- **Testing and debugging**

Multi-Thread Models

User Threads and Kernel Threads

- **User threads**
  - Thread management done by user-level threads library
  - Ex: POSIX Pthreads, Win32 threads, Java threads

- **Kernel threads**
  - Supported by kernel (OS) directly
  - Ex: Windows 2000 (NT), Solaris, Linux, Tru64 UNIX

- Programmers create **user threads** using thread APIs and then the threads are bounded to **kernel threads** by the OS

User Threads and Kernel Threads (cont.)

- **User threads**
  - Thread library provides support for thread creation, scheduling, and deletion
  - Generally fast to create and manage
  - If the kernel is single-threaded,

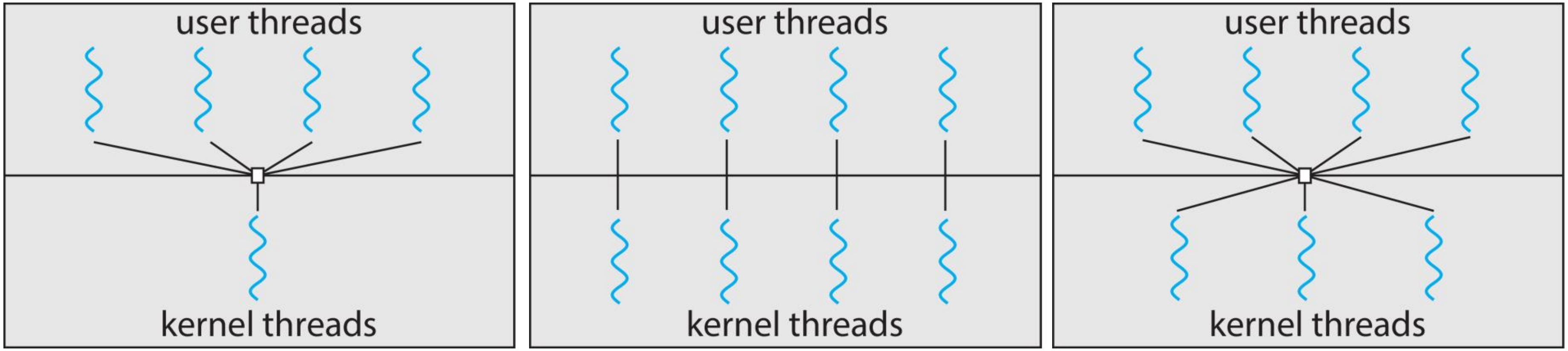
    a user thread blocks ➔ entire process blocks

    even if other threads are ready to run

- **Kernel threads**
  - The kernel performs thread creation, scheduling, etc.
  - Generally slower to create and manage
  - If a thread is blocked, the kernel can schedule another thread for execution

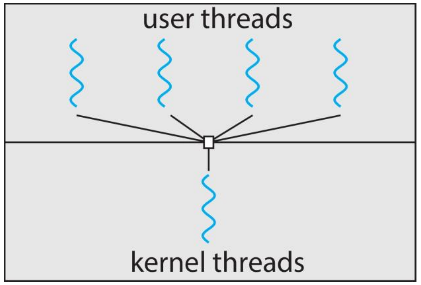
Multi-Threading Models

- **Many-to-One**
- **One-to-One**
- **Many-to-Many**



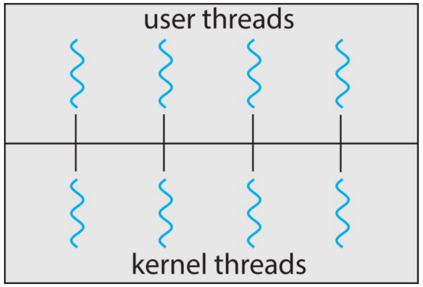
Many-to-One

- Many user-level threads mapped to a single kernel thread
- Used on systems that do not support kernel threads
- The entire process will block if a thread makes a blocking system call
- Only one thread can access the kernel at a time
  - Multiple threads are unable to run in parallel on multi-processors



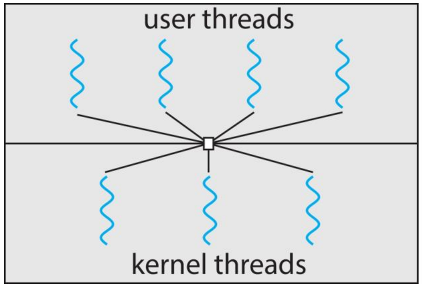
One-to-One

- Each user-level thread maps to a kernel thread
  - Creating a user-level thread creates a kernel thread
  - There could be a limit on number of kernel threads (high overhead)
- More concurrency
- Examples
  - Windows
  - Linux
  - Solaris 9 and later



Many-to-Many

- Multiplexes many user-level threads to a smaller or equal number of kernel threads
- Allow the developer to create as many user threads as wished
- The corresponding kernel threads can run in parallel on a multi-processor
- When a thread performs a blocking call, the kernel can schedule another for execution



Thread Case Study

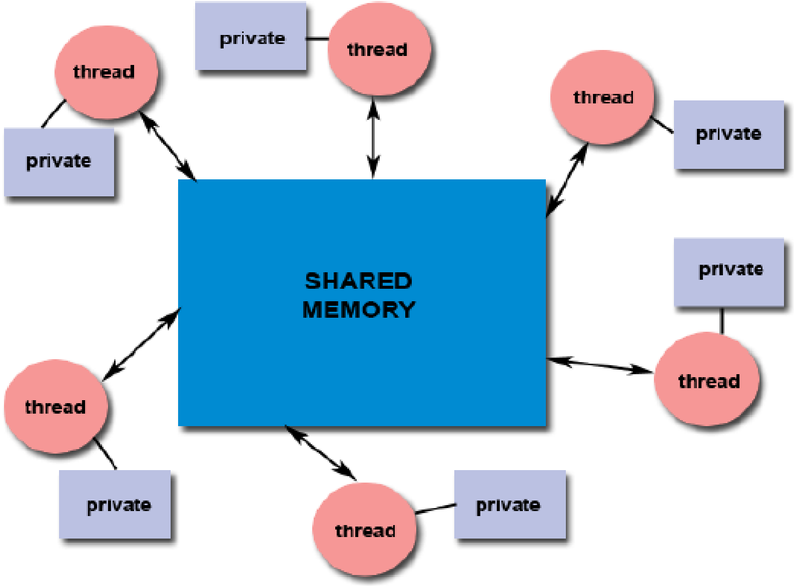
Case Study

- Thread libraries
  - Pthreads
  - Java threads

- OS examples
  - Linux

Shared-Memory Programming

- **Definition**
  - Processes communicate or work together with each other through a shared memory space which can be accessed by all processes
  - Usually faster and more efficient than message passing
- **Issues**
  - Synchronization
  - Deadlock
  - Cache coherence
- **Programming techniques**
  - Parallelizing compiler
  - UNIX processes
  - Threads (Pthreads, Java)

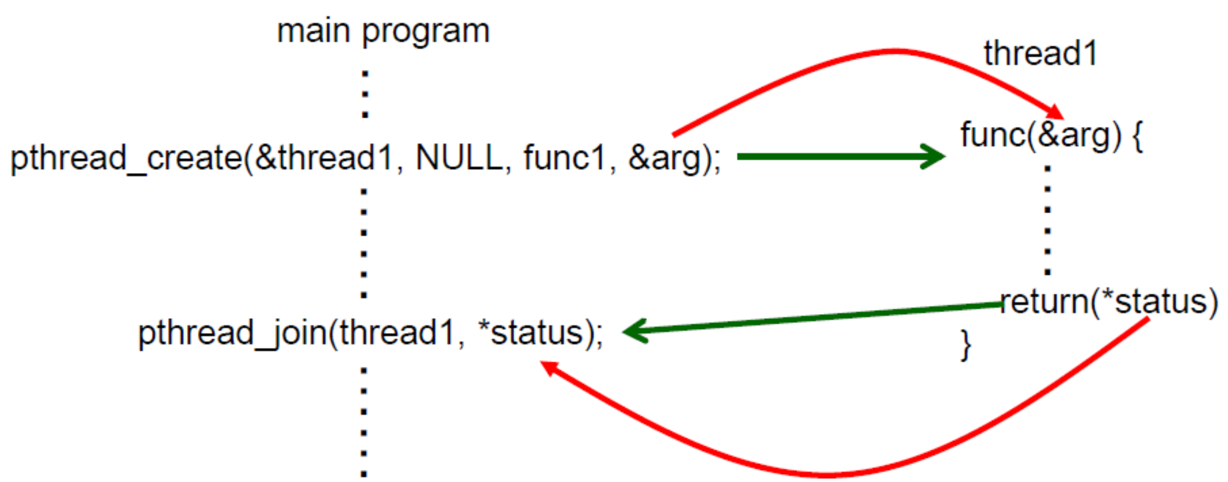


Pthread

- Historically, hardware vendors have implemented their own proprietary versions of threads
- **POSIX** (Portable Operating System Interface) standard is specified for portability across UNIX-like system
- Pthread is the implementation of POSIX standard for thread

Pthread Creation

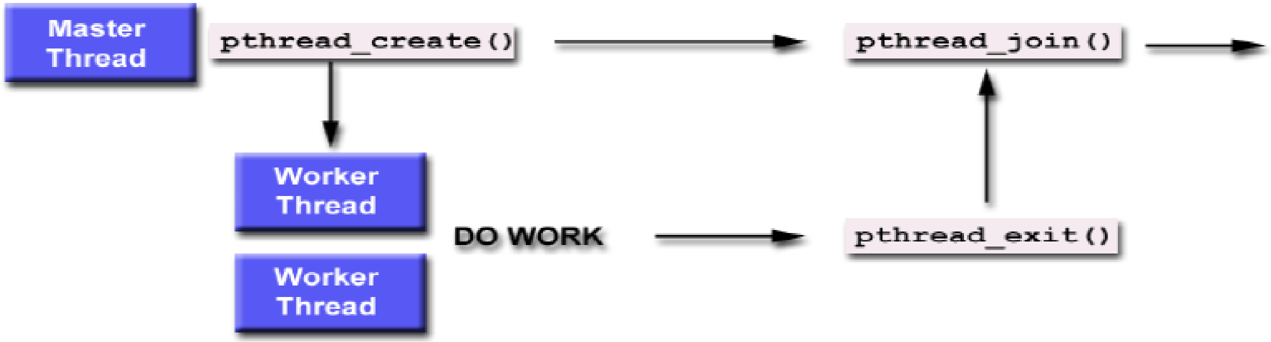
- Library call: ***pthread_create(thread, attr, routine, arg)***
  - *thread*: an unique identifier (token) for the new thread
  - *attr*: used to set thread attributes
  - *routine*: the routine that the thread will execute once it is created
  - *arg*: a single argument that may be passed to routine



Pthread Joining and Detaching

- Library call: ***pthread_join(threadId, status)***
  - Blocks until the specified thread (threadId) terminates
  - One way to accomplish synchronization between threads
  - Example:

    for (int i = 0; i < n ; ++i) pthread_join(thread[i], NULL);
- Library call: ***pthread_detach(threadId)***
  - Once a thread is detached, it can never be joined
  - Detach a thread could free some system resources



Example: PThread

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

#include <stdlib.h>

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

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

  /* set the default attributes of the thread */
  pthread_attr_init(&attr);
  /* create the thread */
  pthread_create(&tid, &attr, runner, argv[1]);
  /* wait for the thread to exit */
  pthread_join(tid,NULL);

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

Example: Pthread (cont.)

```
/* The thread will execute 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);
}
```

Example: Windows Thread

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

/* The thread will execute in this function */
DWORD WINAPI Summation(LPVOID Param)
{
   DWORD Upper = *(DWORD*)Param;
   for (DWORD i = 1; i <= Upper; i++)
      Sum += i;
   return 0;
}
```

Example: Windows Thread (cont.)

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

   Param = atoi(argv[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 */

    /* 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 implemented using a thread library on the host system
  - Win32 threads on Windows
  - Pthreads on UNIX-like system

- Thread mapping depends on implementation of the java virtual machine
  - Windows 98/NT: one-to-one model
  - Solaris2: many-to-many model

Linux Kernel Threads

- Linux does not support multithreading (in the view of OS)
- Various Pthreads implementation are available for user-level
- **The fork system call**
  - Create a new process and a copy of the associated data of the parent process
- **The clone system call**
  - Create a new process and a link that points to the associated data of the parent process

Linux Threads (cont.)

- A set of **flags** is used in the clone system call for indication of the level of the sharing
  - None of the flags is set ➔ clone = fork
  - All flats are set ➔ parent and child share everything

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.

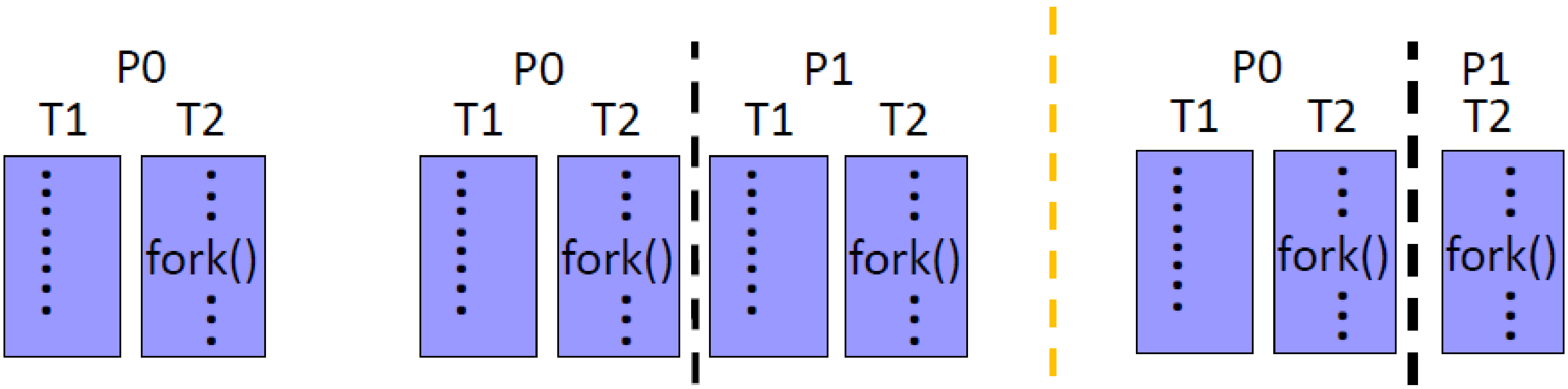
Threading Issues

Threading Issues

- **Semantics of fork() and exec() system calls**
  - Duplicate all the threads or not
- **Thread cancellation**
  - Asynchronous or deferred
- **Signal handling**
  - Where should a signal be delivered
- **Thread pools**
  - Create a number of threads at process startup

Semantics of fork() and exec()

- Does ***fork()*** duplicate only the calling thread or all threads?
  - Some UNIX systems support two versions of fork()
- ***execlp()*** works the same; replace the **entire** process



Thread Cancellation

- What happen if a thread terminates before it has completed
  - Example: terminate web page loading
- **Target thread**: a thread that is to be cancelled
- Two general approaches
  - **Asynchronous cancellation**
    - One thread terminates the target thread immediately
  - **Deferred cancellation (default option)**
    - The target thread periodically checks whether it should be terminated, allowing it an opportunity to terminate itself in an orderly fashion (canceled safely)
    - Check at cancellation point

Signal Handing

- Signals are used in UNIX systems to notify a process that a particular event has occurred
  - **Synchronous**: illegal memory access
  - **Asynchronous**: e.g., <control-C>

- Where should a signal be delivered for multi-threaded?
  - 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

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 applications to be bound to the size of the pool
- Determine the number of threads
  - Based on number of CPUs, amount of physical memory … etc.

Objectives Review

- Identify the basic components of a thread, and distinguish threads and processes
- Describe the benefits and challenges of designing multi-threaded applications
- Illustrate different approaches to implicit threading including fork-join and thread pools