# Lecture 09: Programming with PThreads

**Concurrent and Multicore Programming**

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# Topics (Part 1)

- Introduction
- Principles of parallel algorithm design (Chapter 3)
- Programming on shared memory system (Chapter 7)
  - **OpenMP**
  - ☛ **PThread, mutual exclusion, locks, synchronizations**
  - **Cilk/Cilkplus**
- Analysis of parallel program executions (Chapter 5)
  - **Performance Metrics for Parallel Systems**
    - **Execution Time, Overhead, Speedup, Efficiency, Cost**
  - **Scalability of Parallel Systems**
  - **Use of performance tools**

# Short Review

- Parallel algorithm design
  1. Tasks and Decomposition
     - Theory and practice (axpy, matvec and matmul)
  2. **Processes and Mapping**
  3. Minimizing Interaction Overheads

- Practice on **task and decomposition**
  – AXPY, Matrix vector multiplication, matrix matrix multiplication

# OpenMP: Worksharing Constructs

Sequential code

```
for(i=0;i<N;i++)   { a[i] = a[i] + b[i]; }
```

OpenMP parallel region

```
#pragma omp parallel shared (a, b)

{

      int id, i, Nthrds, istart, iend;
      id = omp_get_thread_num();
      Nthrds = omp_get_num_threads();
      istart = id * N / Nthrds;
      iend = (id+1) * N / Nthrds;
      for(i=istart;i<iend;i++)   { a[i] = a[i] + b[i]; }
}
```

OpenMP parallel region and a worksharing for construct

```
#pragma omp parallel shared (a, b) private (i)
#pragma omp for schedule(static)
      for(i=0;i<N;i++)   { a[i] = a[i] + b[i]; }
```

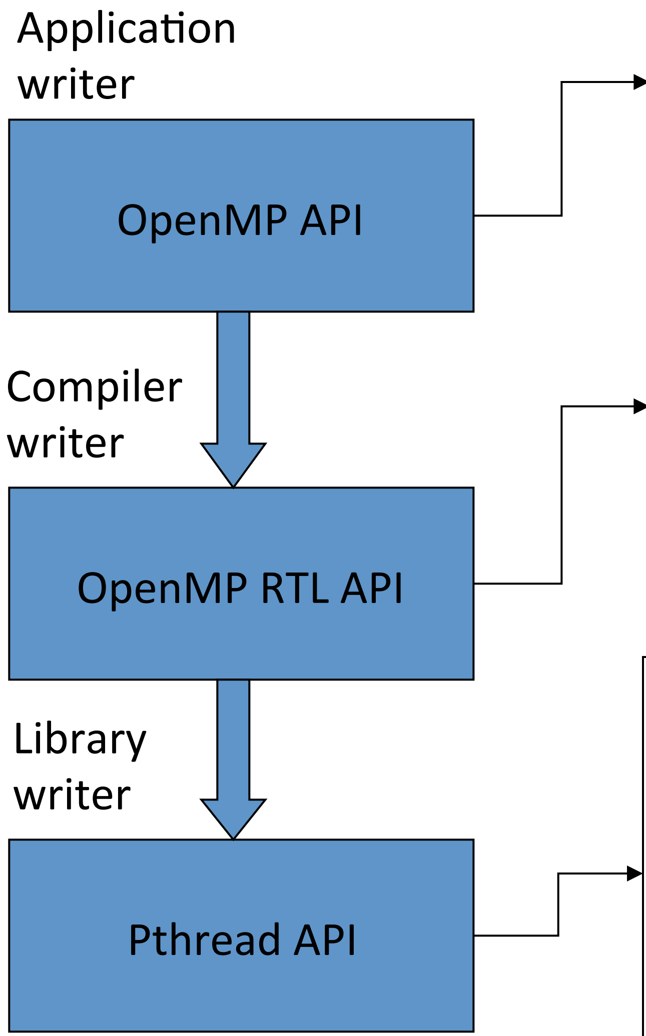
# Standard OpenMP Implementation

- Directives implemented via code modification and insertion of runtime library calls
  - Basic step is outlining of code in parallel region
- Runtime library responsible for managing threads
  - Scheduling loops
  - Scheduling tasks
  - Implementing synchronization
- Implementation effort is reasonable

| OpenMP Code | Translation |
| --- | --- |
| int main(void)<br>{<br>int a,b,c;<br>#pragma omp parallel \ <br>private(c)<br>do_sth(a,b,c);<br>return 0;<br>} | _INT32 main()<br>{<br>int a,b,c;<br>/* microtask */<br>void **__ompregion_main1**()<br>{<br>_INT32 __mplocal_c;<br>/*shared variables are kept intact, substitute accesses to private variable*/<br>do_sth(a, b, __mplocal_c);<br>}<br>…<br>/*OpenMP runtime calls */<br>__ompc_fork(&**__ompregion_main1**<br>);<br>…<br>} |

Each compiler has custom run-time support. Quality of the runtime system has major impact on performance.

# OpenMP Implementation

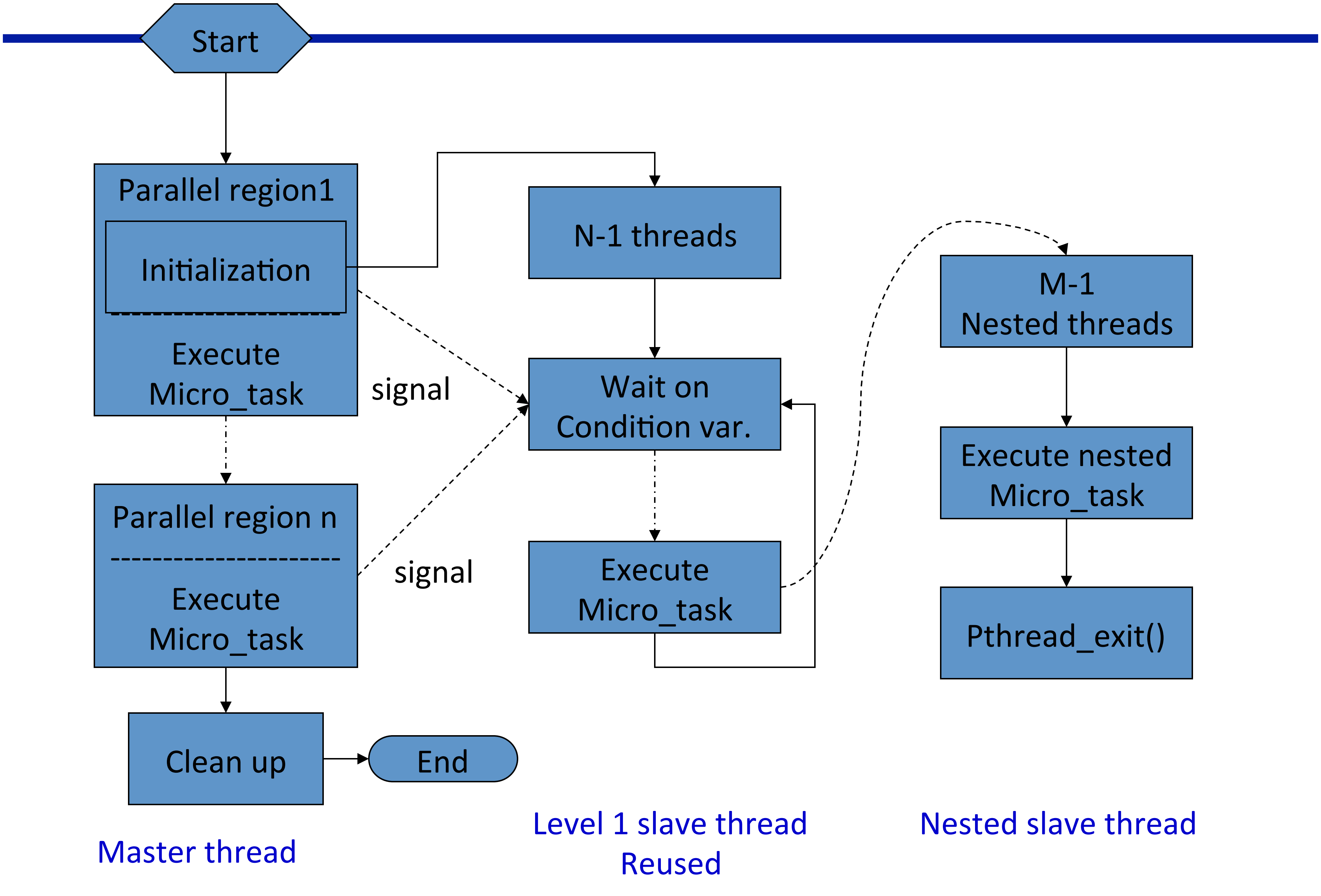



```
main () {
        #pragma omp parallel
        printf("Hello,world.!\n");
```

```
main () {  …
 __ompc_fork(0, &__ompregion_main1,
                 reg__7);
… }
void __ompregion_main1(__ompv_gtid_a__0,
                   __ompv_slink_a__0)
{…
 printf((const _INT8 *)(_INT8(*)[15LL]) "Hello,world.!\n");
}
```

```
….
for (i=1; i< threads_to_create; i++)
{ return_value = pthread_create(
        &(__omp_level_1_pthread[i].uthread_id),
        &__omp_pthread_attr,
        (pthread_entry) __ompc_level_1_slave,
        (void *)((unsigned long int)i));
…
```

# Execution Model



# PThread

- **Processing Element abstraction for software**
  - PThreads
  - OpenMP/Cilk/others runtime use PThreads for their implementation
- **The foundation of parallelism from computer system**
- **Topic Overview**
  - Thread basics and the POSIX Thread API
  - Thread creation, termination and joining
  - Thread safety
  - Synchronization primitives in PThreads

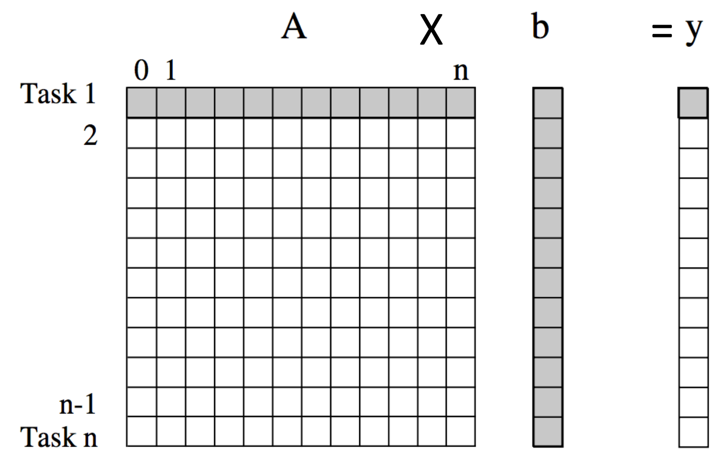
# What is a Thread

- OS view
  - An independent stream of instructions that can be scheduled to run by the OS.
- Software developer view
  - A "procedure" that runs independently from the main program
    - Imagine multiple such procedures of main run simultaneously and/or independently
  - Sequential program: a single stream of instructions in a program.
  - Multi-threaded program: a program with multiple streams
    - Multiple threads are needed to use multiple cores/CPUs

- **A thread is a virtual representation of a hardware core**

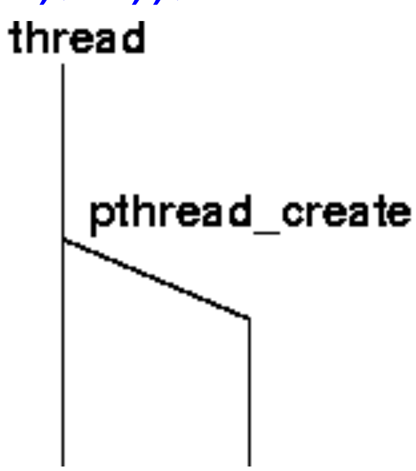
# Thread as “function instance”

**A *thread* is a single stream of control in the flow of a program:**




```
for (i = 0; i < n; i++)
  y[i] = dot_product(row(A, i),b);
```

```
for (i = 0; i < n; i++)
   y[i] = create_thread(dot_product(row(A, i), b));
```




- think of the thread as an instance of a function that returns before the function has finished executing.

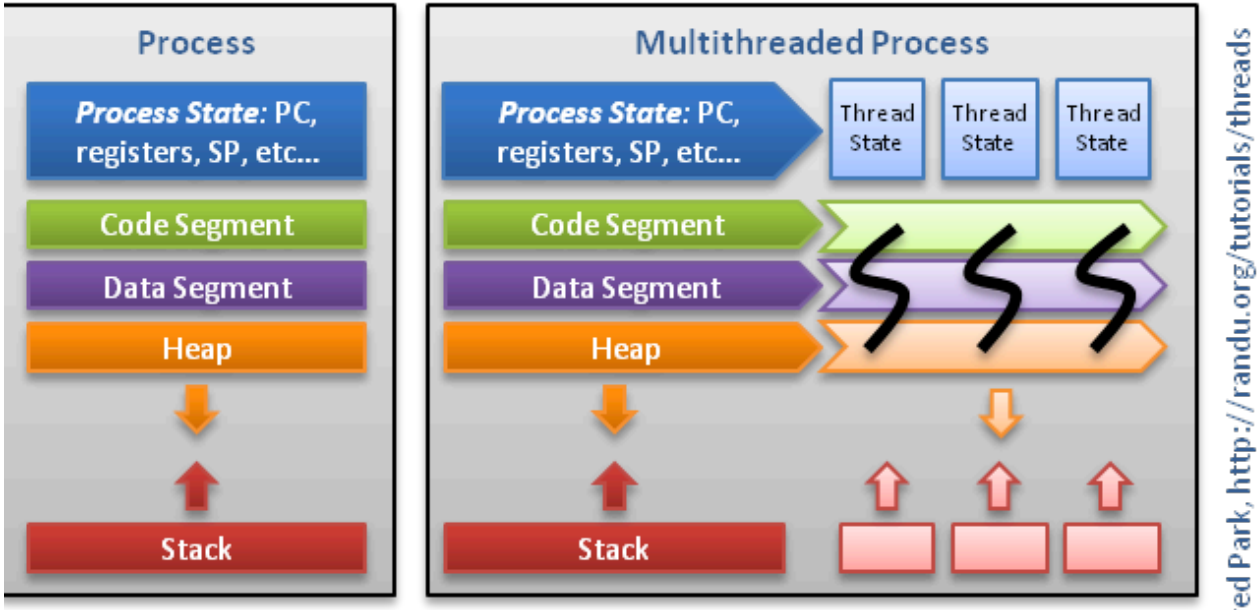
# Processes

- **processes** contain information about program resources and program execution state, including:
  - Process ID, process group ID, user ID, and group ID
  - Environment, Working directory, Program instructions
  - Registers, Stack, Heap
  - File descriptors, Signal actions
  - Shared libraries, Inter-process communication tools (such as message queues, pipes, semaphores, or shared memory).

- When we run a program, a process is created
  - E.g. ./a.out, ./axpy, etc
  - fork () system call

# Threads

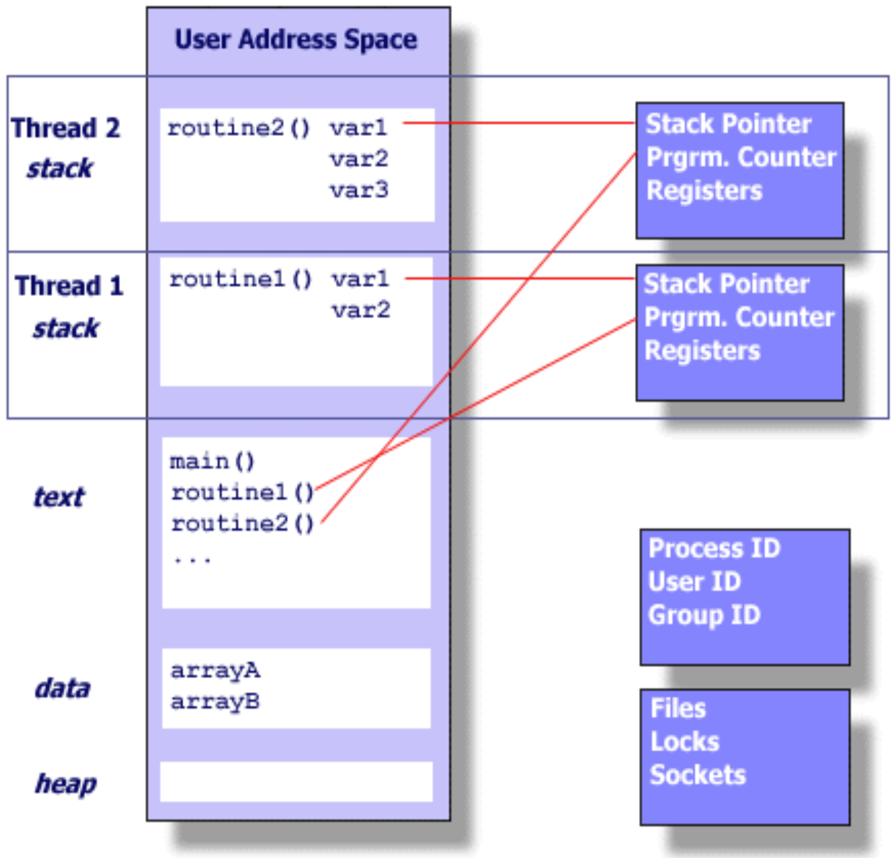
- Threads use, and exist within, the process resources
- Scheduled and run as independent entities
- Duplicate only the bare essential resources that enable them to exist as executable code




Threads contain only necessary information, such as a stack (for local variables, function arguments, return values), a copy of the registers, program counter and any thread-specific data to allow them to be scheduled individually. Other data is shared within the process between all threads.

# Threads

- A thread maintains its own:
  - Stack pointer
  - Registers
  - Scheduling properties (such as policy or priority)
  - Set of pending and blocked signals
  - Thread specific data.
- Multiple threads share the process resources
- A thread dies if the process dies
- "lightweight" for creating and terminating threads that for processes



# POSIX threads (Pthreads)

- Threads used to implement parallelism in shared memory multiprocessor systems, such as SMPs
- Historically, hardware vendors have implemented their own proprietary versions of threads
  - Portability a concern for software developers.
- For UNIX systems, a standardized C language threads programming interface has been specified by the IEEE POSIX 1003.1c standard.
  - Implementations that adhere to this standard are referred to as **POSIX threads**

# The POSIX Thread API

- Commonly referred to as Pthreads, POSIX has emerged as the standard threads API, supported by most vendors.
  - Implemented with a pthread.h header/include file and a thread library

- Functionalities
  - Thread management, e.g. creation and joining
  - Thread synchronization primitives
    - Mutex
    - Condition variables
    - Reader/writer locks
    - Pthread barrier
  - Thread-specific data

- The concepts discussed here are largely independent of the API
  - Applied to other thread APIs (NT threads, Solaris threads, Java threads, etc.) as well.

# PThread API

- `#include <pthread.h>`

| Routine Prefix | Functional Group |
|---|---|
| **pthread_** | Threads themselves and miscellaneous subroutines |
| **pthread_attr_** | Thread attributes objects |
| **pthread_mutex_** | Mutexes |
| **pthread_mutexattr_** | Mutex attributes objects. |
| **pthread_cond_** | Condition variables |
| **pthread_condattr_** | Condition attributes objects |
| **pthread_key_** | Thread-specific data keys |

- **`gcc -lpthread`**

# Thread Creation

- Initially, main() program comprises a single, default thread
  - All other threads must be explicitly created

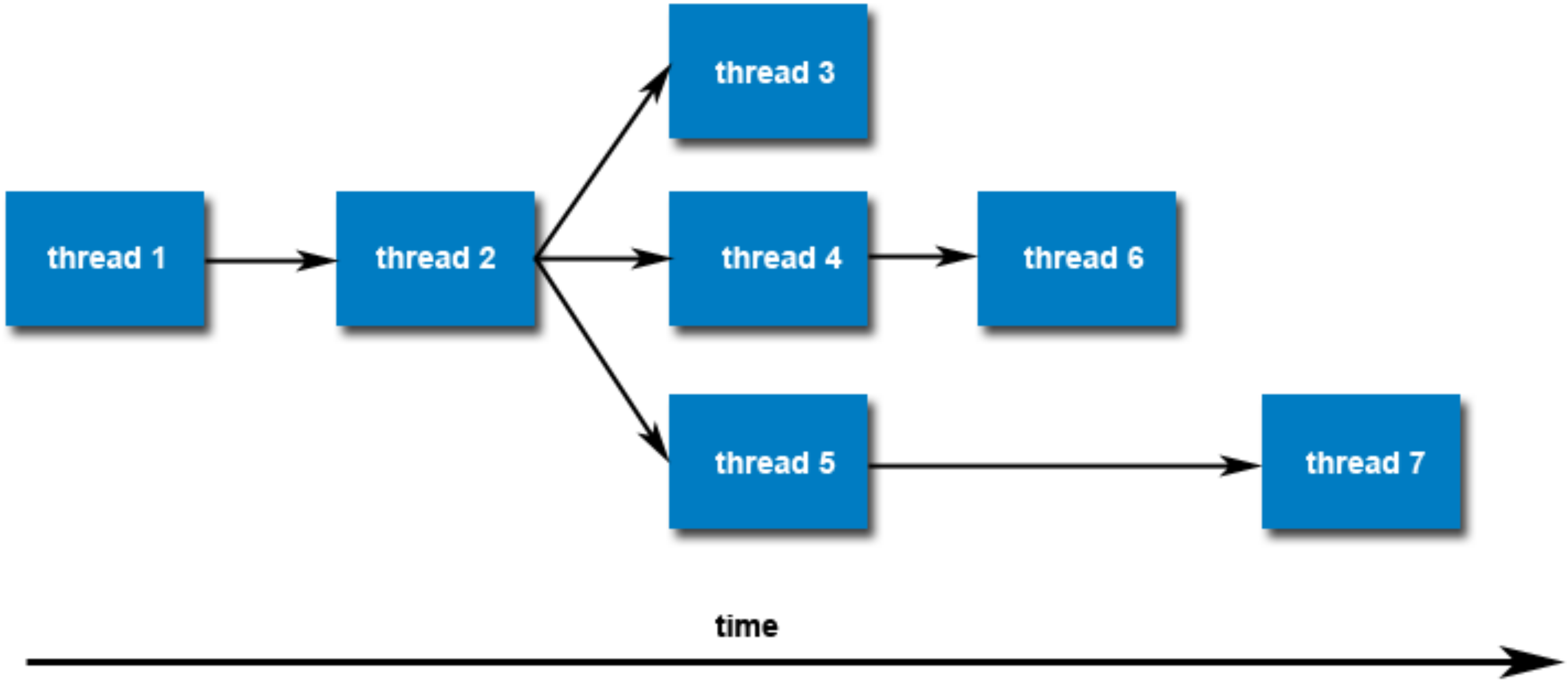
```
int pthread_create(
    pthread_t *thread,
    const pthread_attr_t *attr,
    void *(*start_routine)(void *),
    void * arg);
```

- **thread**: An *opaque*, unique identifier for the new thread returned by the subroutine
- **attr**: An *opaque* attribute object that may be used to set thread attributes
  You can specify a thread attributes object, or NULL for the default values
- **start_routine**: the C routine that the thread will execute once it is created
- **arg:** A single argument that may be passed to *start_routine*. It must be passed by reference as a pointer cast of type void. NULL may be used if no argument is to be passed.

Opaque object: A letter is an opaque object to the mailman, and sender and receiver know the information.

# Thread Creation

- **pthread_create** creates a new thread and makes it executable, i.e. run immediately in theory
  - can be called any number of times from anywhere within your code
- Once created, threads are peers, and may create other threads
- There is no implied hierarchy or dependency between threads



# Example 1: pthread_create

```
#include <pthread.h>
#define NUM_THREADS 5

void *PrintHello(void *thread_id) {
   long tid = (long)thread_id;
   printf("Hello World! It's me, thread #%ld!\n", tid);
   pthread_exit(NULL);
}

int main(int argc, char *argv[]) {
   pthread_t threads[NUM_THREADS];
   long t;

   for(t=0;t<NUM_THREADS;t++) {
      printf("In main: creating thread %ld\n", t);
      int rc = pthread_create(&threads[t], NULL, PrintHello, (void *)t );
      if (rc) {
          printf("ERROR; return code from pthread_create() is %d\n", rc);
          exit(-1);
      }
   }
  pthread_exit(NULL);
}
```

```
One possible output:

In main: creating thread 0
In main: creating thread 1
In main: creating thread 2
In main: creating thread 3
Hello World! It's me, thread #0!
In main: creating thread 4
Hello World! It's me, thread #1!
Hello World! It's me, thread #3!
Hello World! It's me, thread #2!
Hello World! It's me, thread #4!
```

# Terminating Threads

- **`pthread_exit`** is used to explicitly exit a thread
  - Called after a thread has completed its work and is no longer required to exist
- If `main()` finishes before the threads it has created
  - If exits with pthread_exit(), the other threads will continue to execute
  - Otherwise, they will be automatically terminated when `main()` finishes
- The programmer may optionally specify a termination *status*, which is stored as a void pointer for any thread that may join the calling thread
- Cleanup: the `pthread_exit()` routine does not close files
  - Any files opened inside the thread will remain open after the thread is terminated

# Thread Attribute

```
int pthread_create(
      pthread_t *thread,
      const pthread_attr_t *attr,
      void *(*start_routine)(void *),
      void * arg);
```

- Attribute contains details about
  - whether scheduling policy is inherited or explicit
  - scheduling policy, scheduling priority
  - stack size, stack guard region size

- **`pthread_attr_init`** and **`pthread_attr_destroy`** are used to initialize/destroy the thread attribute object
- Other routines are then used to query/set specific attributes in the thread attribute object

# Passing Arguments to Threads

- The `pthread_create()` routine permits the programmer to pass **one** argument to the thread start routine
- For cases where multiple arguments must be passed:
  - Create a structure which contains all of the arguments
  - Then pass a pointer to the object of that structure in the `pthread_create()` routine.
  - All arguments must be passed by reference and cast to (void *)

- Make sure that all passed data is thread safe: data racing
  - it can not be changed by other threads
  - It can be changed in a determinant way
    - Thread coordination

# Example 2: Argument Passing

```
#include <pthread.h>
#define NUM_THREADS 8

struct thread_data {
   int  thread_id;
   char *message;
};

struct thread_data thread_data_array[NUM_THREADS];

void *PrintHello(void *threadarg) {
   int taskid;
   char *hello_msg;

   sleep(1);
   struct thread_data *my_data = (struct thread_data *) threadarg;
   taskid = my_data->thread_id;
   hello_msg = my_data->message;
   printf("Thread %d: %s\n", taskid, hello_msg);
   pthread_exit(NULL);
}
```

# Example 2: Argument Passing

```
int main(int argc, char *argv[]) {
    pthread_t threads[NUM_THREADS];
    int t;
    char *messages[NUM_THREADS];
    messages[0] = "English: Hello World!";
    messages[1] = "French: Bonjour, le monde!";
    messages[2] = "Spanish: Hola al mundo";
    messages[3] = "Klingon: Nuq neH!";
    messages[4] = "German: Guten Tag, Welt!";
    messages[5] = "Russian: Zdravstvytye, mir!";
    messages[6] = "Japan: Sekai e konnichiwa!";
    messages[7] = "Latin: Orbis, te saluto!";

    for(t=0;t<NUM_THREADS;t++) {
      struct thread_data * thread_arg = &thread_data_array[t];
      thread_arg->thread_id = t;
      thread_arg->message = messages[t];
      pthread_create(&threads[t], NULL, PrintHello, (void *) thread_arg);
    }
    pthread_exit(NULL);
}
```

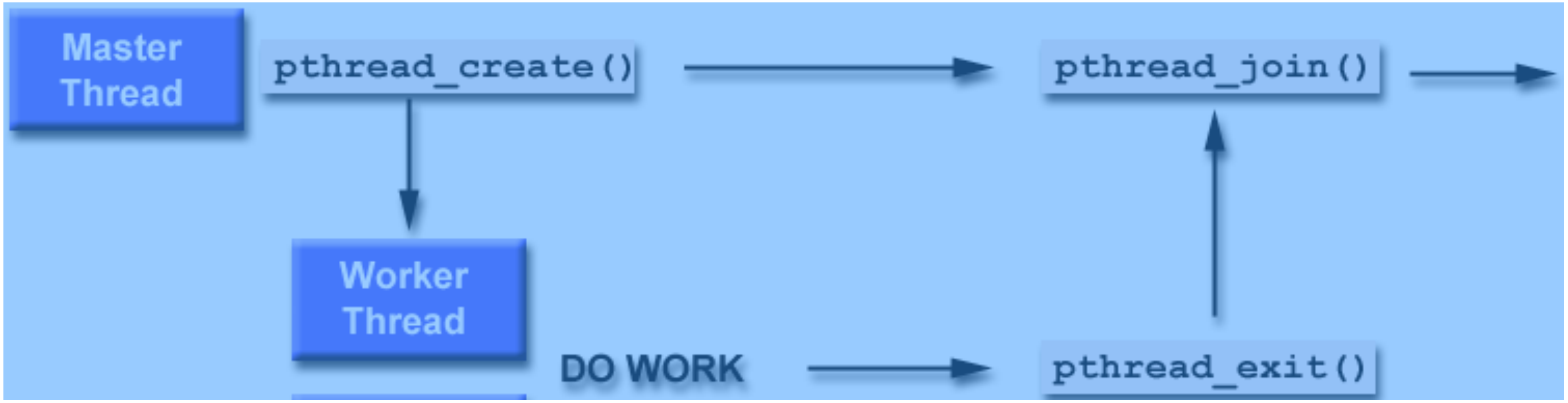
```
Thread 3: Klingon: Nuq neH!
Thread 0: English: Hello World!
Thread 1: French: Bonjour, le monde!
Thread 2: Spanish: Hola al mundo
Thread 5: Russian: Zdravstvytye, mir!
Thread 4: German: Guten Tag, Welt!
Thread 6: Japan: Sekai e konnichiwa!
Thread 7: Latin: Orbis, te saluto!
```

# Wait for Thread Termination

**Suspend execution of calling thread until thread terminates**

```
#include <pthread.h>
int pthread_join(
   pthread_t thread,
   void **value_ptr);
```

- **thread:** the joining thread
- **value_ptr**: ptr to location for return code a terminating thread passes to pthread_exit




- It is a logical error to attempt simultaneous multiple joins on the same thread

# Example 3: Pthread Joining

```
#include <pthread.h>
#define NUM_THREADS 4

void *BusyWork(void *t) {
    int i;
    long tid = (long)t;
    double result=0.0;
    printf("Thread %ld starting...\n",tid);
    for (i=0; i<1000000; i++)  {
        result = result + sin(i) * tan(i);
    }
    printf("Thread %ld done. Result = %e\n",tid, result);
    pthread_exit((void*) t);
}
```

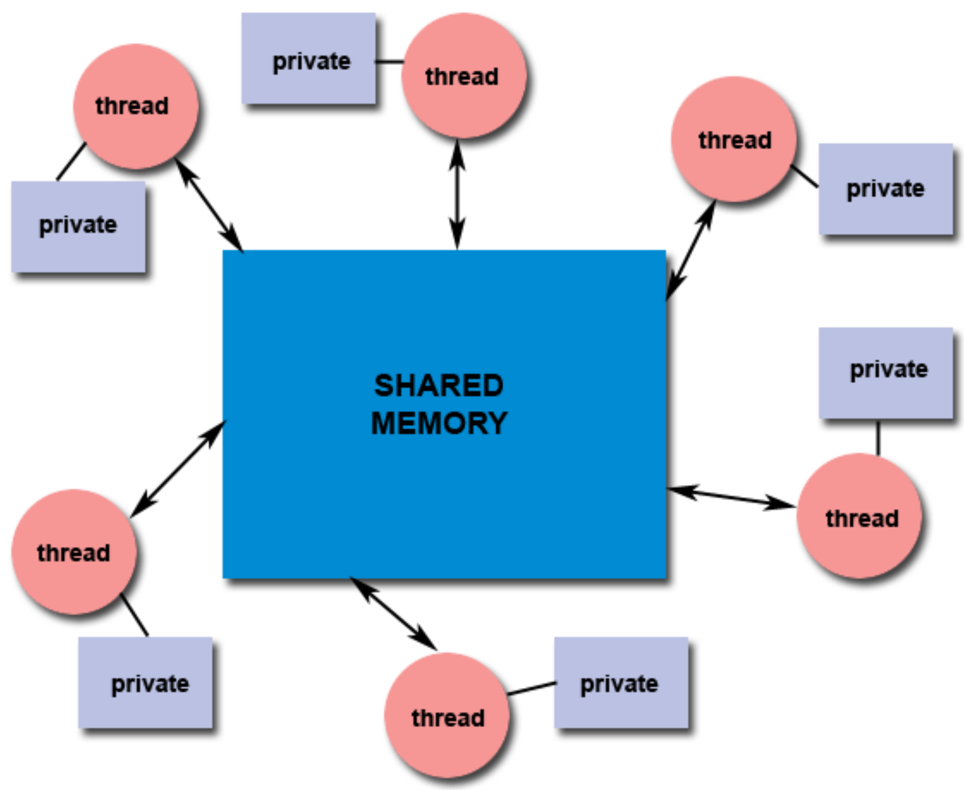
# Example 3: Pthread joining

```
int main (int argc, char *argv[])
{
  pthread_t thread[NUM_THREADS];
  pthread_attr_t attr;
  long t;
  void *status;

  /* Initialize and set thread detached attribute */
  pthread_attr_init(&attr);
  pthread_attr_setdetachstate(&attr, PTHREAD_C

  for(t=0; t<NUM_THREADS; t++) {
    printf("Main: creating thread %ld\n", t);
    pthread_create(&thread[t], &attr, BusyWork, (v
  }
  /* Free attribute and wait for the other threads */
  pthread_attr_destroy(&attr);
  for(t=0; t<NUM_THREADS; t++) {
    pthread_join(thread[t], &status);
    printf("Main: joined with thread %ld, status: %ld\n", t, (long)status);
  }
  printf("Main: program completed. Exiting.\n");
  pthread_exit(NULL);
}
```

```
Main: creating thread 0
Main: creating thread 1
Thread 0 starting...
Main: creating thread 2
Thread 1 starting...
Main: creating thread 3
Thread 2 starting...
Thread 3 starting...
Thread 1 done. Result = -3.153838e+06
Thread 0 done. Result = -3.153838e+06
Main: joined with thread 0, status: 0
Main: joined with thread 1, status: 1
Thread 2 done. Result = -3.153838e+06
Main: joined with thread 2, status: 2
Thread 3 done. Result = -3.153838e+06
Main: joined with thread 3, status: 3
Main: program completed. Exiting.
```

# Shared Memory and Threads

- All threads have access to the same global, shared memory
- Threads also have their own private data
- Programmers are responsible for synchronizing access (protecting) globally shared data.



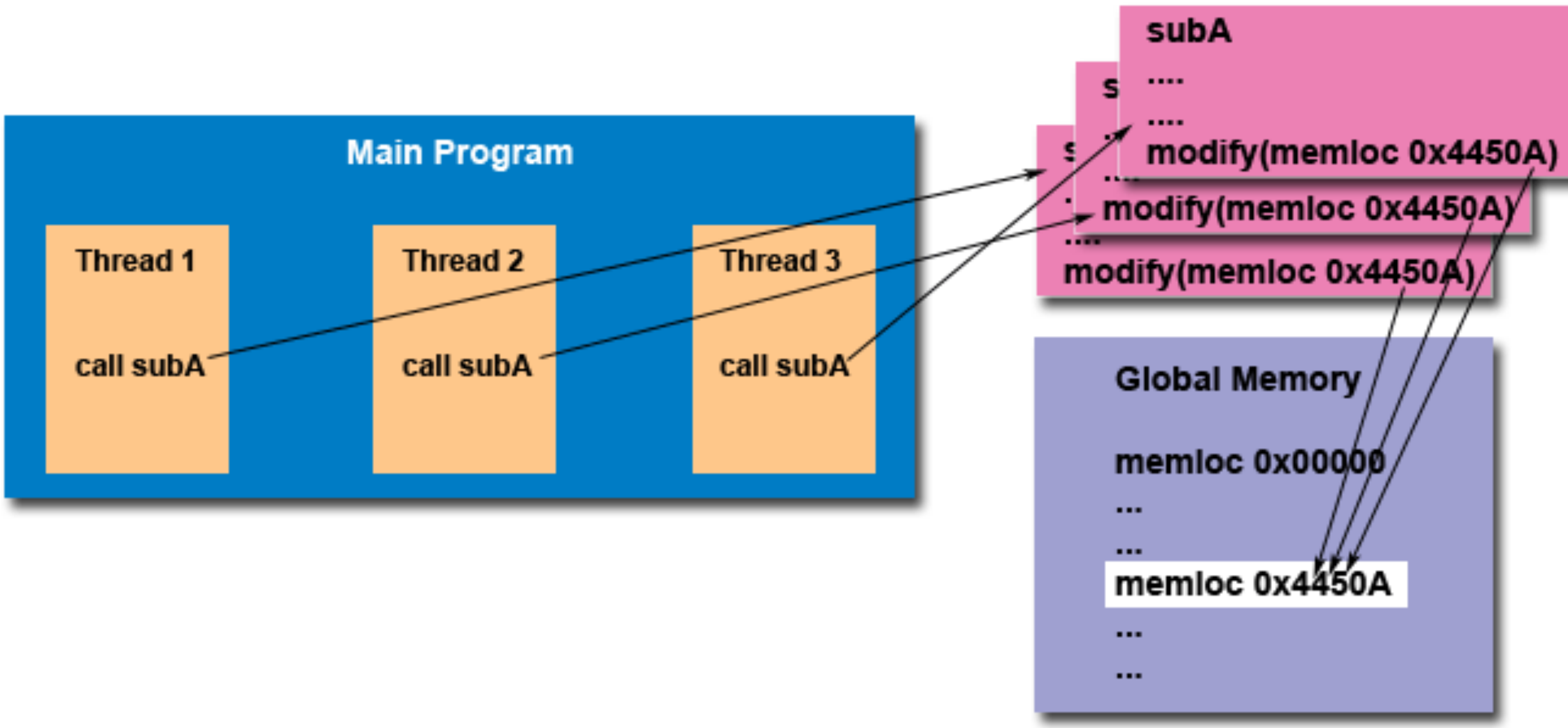
# Thread Consequences

- Shared State!
  - Accidental changes to global variables can be fatal.
  - Changes made by one thread to shared system resources (such as closing a file) will be seen by all other threads
  - Two pointers having the same value point to the same data
  - Reading and writing to the same memory locations is possible
  - Therefore requires explicit synchronization by the programmer
- Many library functions are not thread-safe
  - Library Functions that return pointers to static internal memory. E.g. gethostbyname()
- Lack of robustness
  - Crash in one thread will crash the entire process

# Thread-safeness

- Thread-safeness: in a nutshell, refers an application's ability to execute multiple threads simultaneously without "clobbering" shared data or creating "race" conditions
- Example:  an application creates several threads, each of which makes a call to the same library routine:
  - This library routine accesses/modifies a global structure or location in memory.
  - As each thread calls this routine it is possible that they may try to modify this global structure/memory location at the same time.
  - If the routine does not employ some sort of synchronization constructs to prevent data corruption, then it is not thread-safe.

# Thread-safeness



# Thread-safeness

**The implication to users of external library routines:**

- If you aren't 100% certain the routine is thread-safe, then you take your chances with problems that could arise.

- **Recommendation**
  - Be careful if your application uses libraries or other objects that don't explicitly guarantee thread-safeness.
  - When in doubt, assume that they are not thread-safe until proven otherwise
  - This can be done by "serializing" the calls to the uncertain routine, etc.

# Example 4: Data Racing

```
#include <pthread.h>
#define NUM_THREADS 5

void *PrintHello(void *thread_id) { /* thread func */
   long tid = *((long*)thread_id);
   printf("Hello World! It's me, thread #%ld!\n", tid);
   pthread_exit(NULL);
}

int main(int argc, char *argv[]) {
   pthread_t threads[NUM_THREADS];
   long t;
   for(t=0;t<NUM_THREADS;t++) {
      printf("In main: creating thread %ld\n", t);
      int rc = pthread_create(&threads[t], NULL, PrintHello, (void *)&t );
      if (rc) {
         printf("ERROR; return code from pthread_create() is %d\n", rc);
         exit(-1);
      }
   }
  pthread_exit(NULL);
}
```

In main: creating thread 0
In main: creating thread 1
In main: creating thread 2
In main: creating thread 3
**Hello World! It's me, thread #3!**
**Hello World! It's me, thread #3!**
**Hello World! It's me, thread #3!**
In main: creating thread 4
Hello World! It's me, thread #4!
Hello World! It's me, thread #5!

# Why Pthreads (not processes)?

- The primary motivation
  - To realize potential program performance gains
- Compared to the cost of creating and managing a process
  - A thread can be created with much less OS overhead
- Managing threads requires fewer system resources than managing processes
- All threads within a process share the same address space
- Inter-thread communication is more efficient and, in many cases, easier to use than inter-process communication

# pthread_create vs fork

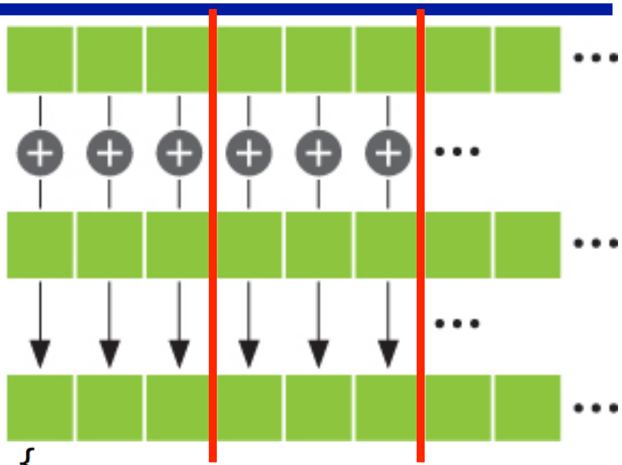
- Timing results for the **fork()** subroutine and the **pthreads_create()** subroutine
  - Timings reflect 50,000 process/thread creations
  - units are in seconds
  - no optimization flags

| Platform | fork() | | | pthread_create() | | |
|---|---|---|---|---|---|---|
| | real | user | sys | real | user | sys |
| AMD 2.4 GHz Opteron (8cpus/node) | 41.07 | 60.08 | 9.01 | 0.66 | 0.19 | 0.43 |
| IBM 1.9 GHz POWER5 p5-575 (8cpus/node) | 64.24 | 30.78 | 27.68 | 1.75 | 0.69 | 1.10 |
| IBM 1.5 GHz POWER4 (8cpus/node) | 104.05 | 48.64 | 47.21 | 2.01 | 1.00 | 1.52 |
| INTEL 2.4 GHz Xeon (2 cpus/node) | 54.95 | 1.54 | 20.78 | 1.64 | 0.67 | 0.90 |
| INTEL 1.4 GHz Itanium2 (4 cpus/node) | 54.54 | 1.07 | 22.22 | 2.03 | 1.26 | 0.67 |

# Why pthreads

- Potential performance gains and practical advantages over non-threaded applications:
  - Overlapping CPU work with I/O
    - For example, a program may have sections where it is performing a long I/O operation
    - While one thread is waiting for an I/O system call to complete, CPU intensive work can be performed by other threads.
- Priority/real-time scheduling
  - Tasks which are more important can be scheduled to supersede or interrupt lower priority tasks.
- Asynchronous event handling
  - Tasks which service events of indeterminate frequency and duration can be interleaved
  - For example, a web server can both transfer data from previous requests and manage the arrival of new requests.

# AXPY with PThreads



- $y = \alpha \cdot x + y$
  - x and y are vectors of size N
    - In C, x[N], y[N]
  - $\alpha$ is scalar
- Decomposition and mapping to pthreads

```
void dist(int tid, int N, int num_tasks, int *Nt, int *start) {
    int remain = N % num_tasks;
    int esize = N / num_tasks;
    if (tid < remain) { /* each of the first remain task has one more element */
        *Nt = esize + 1;
        *start = *Nt * tid;
    } else {
        *Nt = esize;
        *start = esize * tid + remain;
    }
}
void axpy_dist(int N, REAL Y[], REAL X[], REAL a, int num_tasks) {
    int tid;
    for (tid = 0; tid < num_tasks; tid++) {
        int Nt, start;
        dist(tid, N, num_tasks, &Nt, &start);
        axpy_base_sub(start, Nt, N, Y, X, a);
    }
}
```

A task will be mapped to a pthread

# AXPY with PThreads

```
struct axpy_dist_pthread_data {
    int Nt;
    int start;
    int N;
    REAL *Y;
    REAL *X;
    REAL a;
};

void * axpy_thread_func(void * axpy_thread_arg) {
    struct axpy_dist_pthread_data * arg = (struct axpy_dist_pthread_data *) axpy_thread_arg;
    axpy_base_sub(arg->start, arg->Nt, arg->N, arg->Y, arg->X, arg->a);
    pthread_exit(NULL);
}

void axpy_dist_pthread(int N, REAL Y[], REAL X[], REAL a, int num_tasks) {
    struct axpy_dist_pthread_data pthread_data_array[num_tasks];
    pthread_t task_threads[num_tasks];
    int tid;
    for (tid = 0; tid < num_tasks; tid++) {
        int Nt, start;
        dist(tid, N, num_tasks, &Nt, &start);
        struct axpy_dist_pthread_data *task_data = &pthread_data_array[tid];
        task_data->start = start;
        task_data->Nt = Nt;
        task_data->a = a;
        task_data->X = X;
        task_data->Y = Y;
        task_data->N = N;

        pthread_create(&task_threads[tid], NULL, axpy_thread_func, (void*)task_data);
    }

    for (tid = 0; tid < num_tasks; tid++) {
        pthread_join(task_threads[tid], NULL);
    }
}
```