Three Reasons to Study Parallel Programming

1. Increase performance: do more work in the same amount of time
2. Increase performance: take less time to do the same amount of work
3. Make some programming tasks more convenient to implement

Example:
Decrease the time to compute an existing simulation program

Example:
Create a web browser where the tasks of monitoring the user interface, downloading text, and downloading multiple images are happening simultaneously

Two Types of Parallelism:

1. Data Level Parallelism (DLP)
   Threads are executing the same instructions on different data

2. Thread (or Task or Functional) Level Parallelism (TLP)
   Threads are executing different instructions

Flynn’s Taxonomy

SISD
“Normal” single-core CPU
SIMD
GPUs, Special vector CPU instructions
MISD
?????
MIMD
Multiple processors running independently

Von Neumann Architecture:
Basically the fundamental pieces of a CPU have not changed since the 1960s

The “Heap” (the result of a malloc or new call), is in here, along with Globals and the Stack

Other elements:
- Clock
- Registers
- Program Counter
- Stack Pointer

These together are the "state" of the processor
**What Exactly is a Process?**

Processes execute a program in memory. The process keeps a state (program counter, registers, and stack).

- Program and Data in Memory (the heap is here too)
- Registers
- Program Counter
- Stack Pointer

Other elements:
- Clock
- Registers
- Program Counter
- Stack Pointer

**Von Neumann Architecture:**

Basically the fundamental pieces of a CPU have not changed since the 1960s.

- Memory
- Control Unit
- Arithmetic Logic Unit
- Accumulator

The "Heap" (the result of a malloc or new call), is in here, along with Globals and the Stack.

Other elements:
- Clock
- Registers
- Program Counter
- Stack Pointer

What if we include more than one set of these?

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**What Exactly is a Thread?**

Threads are separate independent processes, all executing a common program and sharing memory. Each thread has its own state (program counter, registers, and stack pointer).

- Program and Data in Shared Memory (the heap is shared too)
- Registers
- Program Counter
- Stack Pointer

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**Memory Allocation in a Multithreaded Program**

- One-thread
- Stack
- Program Executable
- Globals
- Heap

- Multiple-threads
- Stack
- Program Executable
- Common Globals
- Common Heap

Don't take this completely literally. The exact arrangement depends on the operating system and the compiler. For example, sometimes the stack and heap are arranged so that they grow towards each other.

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**What Exactly is a Thread?**

A "thread" is an independent path through the program code. Each thread has its own Program Counter, Registers, and Stack Pointer. But, since each thread is executing some part of the same program, each thread has access to the same global data in memory. Each thread is scheduled and swapped just like any other process.

Threads can share time on a single processor. You don't have to have multiple processors (although you can – the multicore topic is coming soon!).

This is useful, for example, in a web browser when you want several things to happen autonomously:
- User interface
- Communication with an external web server
- Web page display
- Image loading
- Animation

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**When is it Good to use Multithreading?**

- When certain operations can become blocked, waiting for something else to happen
- When certain operations can be CPU-intensive
- When certain operations must respond to asynchronous I/O, including the user interface (UI)
- To manage independent behaviors in interactive simulations
- When you want to accelerate a single program on multicore CPU chips

Threads can make it easier to have many things going on in your program at one time and can absorb the dead-time of other threads.
Some Definitions

Atomic  An operation that takes place to completion with no chance of being interrupted by another thread
Barrier  A point in the program where all threads must reach before any of them are allowed to proceed
Coarse-grained parallelism Breaking a task up into a small number of large tasks
Deterministic The same set of inputs always gives the same outputs
Dynamic scheduling Dividing the total number of tasks $T$ up so that each of $N$ available threads has less than $T/N$ sub-tasks to do, and then doing out the remaining tasks to threads as they become available
Fine-grained parallelism Breaking a task up into lots of small tasks

Some More Definitions

Private variable After a fork operation, a variable which has a private copy within each thread
Reduction Combining the results from multiple threads into a single sum or product, continuing to use multithreading. Typically, this is performed so that it takes $O(\log_2 N)$ time instead of $O(N)$ time:
Shared variable After a fork operation, a variable which is shared among threads, i.e., has a single value
Speed-up(N) $T_1 / T_N$
Speed-up Efficiency $\frac{\text{Speed-up}(N)}{N}$
Static Scheduling Dividing the total number of tasks $T$ up so that each of $N$ available threads has exactly $T/N$ sub-tasks to do

Parallel Programming Tips

Tip #1 -- Don’t Keep Internal State

```
int GetLastPositiveNumber( int x )
{
static int savedX;
if( x >= 0 )
savedX = x;
return savedX;
}
```

If you do keep internal state between calls, there is a chance that a second thread will hop in and change it, then the first thread will use that state thinking it has not been changed.

Ironically, some of the standard C functions that we use all the time (e.g., strtok) keep internal state:

```
char * strtok ( char * str,   const char * delims );
```

Tip #1 -- Keep External State Instead

```
char * strtok_r ( char *str,  const char *delims,  char **sret );
```

strtok_r returns its internal state to you so that you can store it locally and then pass it back when you are ready. (The ‘r’ stands for “re-entrant”.)

Moral: if you will be multithreading, don’t use internal static variables to retain state inside of functions.

In this case, using strtok_r is preferred:

```
char * strtok_r ( char *str,  const char *delims,  char **sret );
```

err is returns its internal state to you so that you can store it locally and then pass it back when you are ready. (The ‘r’ stands for “re-entrant”.)
Tip #1 – Keep External State Instead

```
char *retValue1;
char * tok1 = strtok_r(Line1, DELIMS, &retValue1);
while( tok1 != NULL ) {
    . . .
    tok1 = strtok(NULL, DELIMS, &retValue1);
};
```

Tip #2 – Avoid Deadlock

Deadlock is when two threads are each waiting for the other to do something

```
Now, execution order no longer matters!
```

Tip #3 – Avoid Race Conditions

• A Race Condition is where it matters which thread gets to a particular piece of code first.
• This often comes about when one thread is modifying a variable while the other thread is in the midst of using it

A good example of a potential race condition situation is maintaining and using the pointer in a stack data structure:

Thread #1: Pushing:
```
p++ ;
*p = incoming ;
p++
```

Thread #2: Popping:
```
ongoing = *p ;
p--;```

Execution order:

```
1 2 3 4
Thread #1: Pushing:
MutexLock A
{ p++ ;
      *p = incoming ;
    }
p++
Thread #2: Popping:
MutexLock A
{ outgoing = "p" ;
    p--; }
```

Tip #4 – Sending a Message to the Optimizer:
The volatile Keyword

The volatile keyword is used to let the compiler know that another thread might be changing a variable “in the background”, so don’t make any assumptions about what can be optimized away.

```
int val = 0;
. . .
while( val != 0 ) ;
```

A good compiler optimizer will eliminate this code because it “knows” that, for all time, \( val \rightarrow 0 \)

```
volatile int val = 0;
. . .
while( val != 0 ) ;
```

The volatile keyword tells the compiler optimizer that it cannot count on \( val \) being \( 0 \) here
Tip #5 – Beware of False Sharing Caching Issues

Note that using more threads initially gives a drop in performance!

We will get to this in the Caching notes!