Parallel Programming:
Background Information and Tips

Oregon State University
Mike Bailey
mjb@cs.oregonstate.edu

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 a simulation

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

Example:
Increase the resolution, and thus the accuracy, of a simulation

Three Types of Parallelism:
1. Instruction Level Parallelism (ILP)

A program might consist of a continuous stream of assembly instructions, but it is not necessarily executed continuously. Oftentimes it has "pauses", waiting for something to be ready so that it can proceed.

```
A = B + 1;
C = 3;
```

```
Load   B,r0
Add    $1,r0
Store  r0,A
Load   $3,r1
Store  r1,C
```

If B is not already in cache, this instruction will *block* while B is fetched from memory

Out-of-order execution capability will slide instructions up if they can be executed while waiting for the block to end

```
Prefetch B
Load   $3,r1
Store  r1,C
Load   B,r0
Add    $1,r0
Store  r0,A
```

If a compiler does this, it's called ***Static ILP***
If the CPU chip does this, it's called ***Dynamic ILP***

This is all good to know, but it's nothing we can control much of.

Three Types of Parallelism:
2. Data Level Parallelism (DLP)

Executing the same instructions on different parts of the data

```
for( i = 0; i < NUM; i++ )
{
        B[ i ] = sqrt( A[ i ] );
}
```

```
for( i = 0;  i < NUM/3;  i++ )
{
        B[ i ] = sqrt( A[ i ] );
}
```

```
for( i = NUM/3;  i < 2*NUM/3;  i++ )
{
        B[ i ] = sqrt( A[ i ] );
}
```

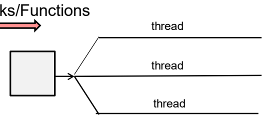
```
for( i = 2*NUM/3;  i < NUM;  i++ )
{
        B[ i ] = sqrt( A[ i ] );
}
```


Three Types of Parallelism:
3. Thread Level Parallelism (TLP)

Executing *different* instructions

Example: processing a variety of incoming transaction requests

Different Tasks/Functions



In general, TLP implies that you have more threads than cores

Thread execution switches when a thread blocks or uses up its time slice

Flynn's Taxonomy

$\left\{\frac{Single}{Multiple}\right\}$ Instruction, $\left\{\frac{Single}{Multiple}\right\}$ Data

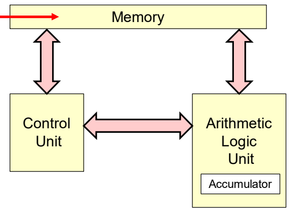
Data →

Instructions ↓

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

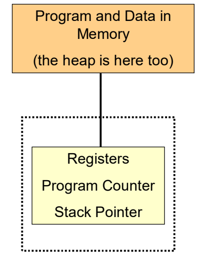


Other elements:
- Clock
- **Registers**
- **Program Counter**
- **Stack Pointer**

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).



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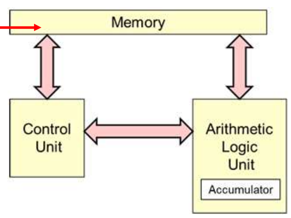
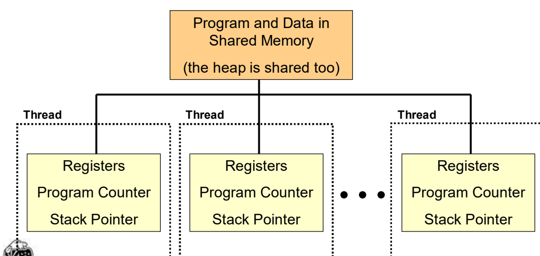


Other elements:
- Clock
- **Registers**
- **Program Counter**
- **Stack Pointer**

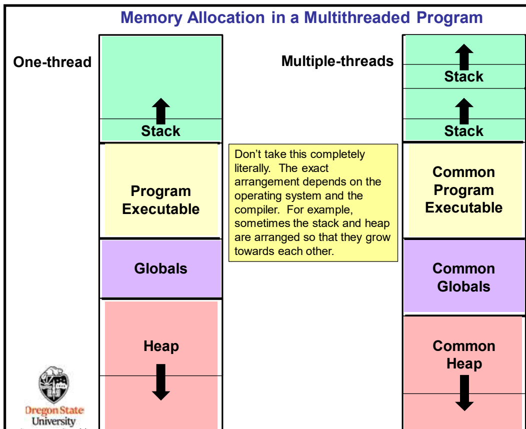
What if we include more than one set of these?

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).



Memory Allocation in a Multithreaded Program



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

When is it Good to use Multithreading?

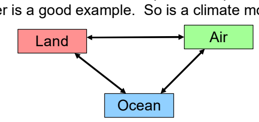
- Where specific operations can become blocked, waiting for something else to happen
- Where specific operations can be CPU-intensive
- Where specific operations must respond to asynchronous I/O, including the user interface (UI)
- Where specific operations have higher or lower priority than other operations
- 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.

Two Ways to Decompose your Problem into Parallelizable Pieces

Functional (or Task) Decomposition

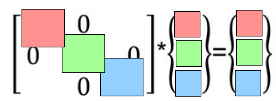
Breaking a task into sub-tasks that represent separate functions.
A web browser is a good example. So is a climate modeling program:



"Thread Parallel"

Domain (or Data) Decomposition

Breaking a task into sub-tasks that represent separate sections of the data. An example is a large diagonally-dominant matrix solution:

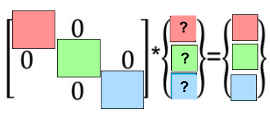


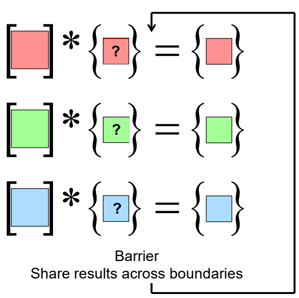
"Data Parallel"

Data Decomposition Reduces the Problem Size per Thread

Example: A diagonally-dominant matrix solution

- Break the problem into blocks
- Solve within the block
- Handle borders separately after a Barrier





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

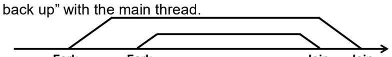
Coarse-grained parallelism Breaking a task up into a small number of large tasks

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 doling out the remaining tasks to threads as they become available

Fine-grained parallelism Breaking a task up into lots of small tasks

Fork-join An operation where multiple threads are created from a main thread. All of those forked threads are expected to eventually finish and thus "join back up" with the main thread.



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 Speed-up(N) / N

Static Scheduling Dividing the total number of tasks T up so that each of N available threads has T/N sub-tasks to do

Parallel Programming Tips

Tip #1 -- Don't Keep Internal State

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```
int
GetLastPositiveNumber( int x )
{
        static int savedX;        <-- Internal state

        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);*

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Tip #1 -- Don't Keep Internal State

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Thread #1

```
char * tok1 = strtok( Line1, DELIMS );      1

while( tok1 != NULL )
{
        . . .
        tok1 = strtok( NULL, DELIMS );      3
};
```

Execution Order

Thread #2

```
char * tok2 = strtok( Line2, DELIMS );      2

while( tok2 != NULL )
{
        . . .
        tok2 = strtok( NULL, DELIMS );
};
```

1. Thread #1 sets the internal character array pointer to somewhere in Line1[ ].
2. Thread #2 resets the same internal character array pointer to somewhere in Line2[ ].
3. Thread #1 uses that internal character array pointer, but it is not pointing into Line1[ ] where Thread #1 thinks it left it.

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Tip #1 -- Keep External State Instead

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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);*

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

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Tip #1 -- Keep External State Instead

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Thread #1

```
char *retValue1;
char * tok1 = strtok_r( Line1, DELIMS, &retValue1 );

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

Thread #2

```
char *retValue2;
char * tok2 = strtok( Line2, DELIMS, &retValue2 );

while( tok2 != NULL )
{
        . . .
        tok2 = strtok( NULL, DELIMS, &retValue2 );
};
```

Execution order no longer matters!

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Tip #1 – Note that Keeping Global State is Just as Dangerous

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Internal state:

```
int
GetLastPositiveNumber( int x )
{
        static int savedX;

        if( x >= 0 )
                savedX = x;

        return savedX;
}
```

Global state:

```
int savedX;

int
GetLastPositiveNumber( int x )
{
        if( x >= 0 )
                savedX = x;

        return savedX;
}
```


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Tip #2 – Avoid Deadlock

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

Worst of all, the way these problems occur is not always deterministic!

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Tip #3 – Avoid Race Conditions

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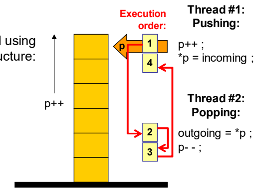
- A Race Condition is where it matters which thread gets to a particular piece of code first.
- This often comes about when one thread is modifying a variable while the other thread is in the midst of using it

A good example is maintaining and using the pointer in a stack data structure:



Worst of all, the way these problems occur is not always deterministic!

BTW, Race Conditions can often be fixed through the use of Mutual Exclusion Locks (Mutexes)

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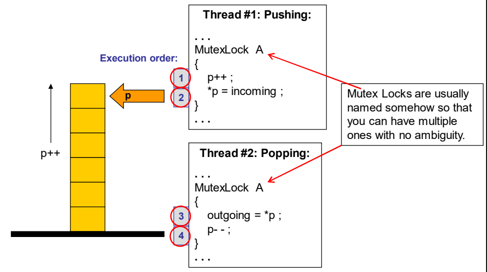

We will talk about these in a little while.
But, note that, while solving a race condition, we can accidentally create a deadlock condition if the thread that owns the lock is waiting for the other thread to do something

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

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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* == 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 -- Sending a Message to the Optimizer: The *restrict* Keyword

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Remember our Instruction Level Parallelism example?

```
A = B + 1;
C = 3;
```

To assembly language

```
Load    B,r0
Add     $1,r0
Store   r0,A
Load    $3,r1
Store   r1,C
```

```
Prefetch B
Load    $3,r1
Store   r1,C
Load    B,r0
Add     $1,r0
Store   r0,A
```

Optimize by moving two instructions up to execute while B is loading

Sending a Message to the Optimizer: The *restrict* Keyword

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```
int *p;
int *q ;
  . . .
p = &B;
q = &B;
A = *p + 1;
*q = 3.;
```

Here the example has been changed slightly. This is what worries the out-of-order mechanisms and keeps them from optimizing as much as they could.

Assembly language

```
Load    [p],r0
Add     $1,r0
Store   r0,A
Load    $3,r1
Store   r1,[q]
```

Using the pointers, and using out-of-order processing

```
Prefetch [p]
Load    $3,r1
Store   r1,[q]
Load    [p],r0
Add     $1,r0
Store   r0,A
```

What's really happening

Prefetch **B**
Load $3,r1
Store r1,**B**
Load **B**,r0
Add $1,r0
Store r0,A

Uh-oh! B is being loaded at the same time it is being stored into.
Who gets there first?
Which value is correct?

Sending a Message to the Optimizer: The *restrict* Keyword

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```
int * restrict p;
int * restrict q;
  . . .
p = &B;
q = &C;
A = *p + 1;
*q = 3.;
```

This is us promising that p and q will *never* point to the same memory location.

Assembly language

```
Load    [p],r0
Add     $1,r0
Store   r0,A
Load    $3,r1
Store   r1,[q]
```

Using the pointers, and using out-of-order processing

```
Prefetch [p]
Load    $3,r1
Store   r1,[q]
Load    [p],r0
Add     $1,r0
Store   r0,A
```

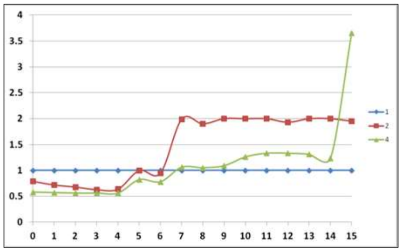
What's really happening

Prefetch **B**
Load $3,r1
Store r1,**C**
Load **B**,r0
Add $1,r0
Store r0,A

Now there is no conflict

Tip #6 – Beware of False Sharing Caching Issues

We will get to this in the Caching notes!



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