Parallel Computing

Parallel Software

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Roadmap

- Parallel software
- Input and output
- Performance
- Parallel program design
- Writing and running parallel programs
- Assumptions
PARALLEL SOFTWARE
The burden is on software

- Hardware and compilers can keep up the pace needed.
- Software needs to be parallel for routine performance increases

Terminology

- In a shared memory program:
  - Start a **single process** and fork **multiple threads**.
  - Threads carry out a **task**.
- In a distributed memory program:
  - Start **multiple processes**.
  - Processes carry out a **task**.
A SPMD program consists of a single executable that can behave as if it were multiple different programs through the use of conditional branches.

```plaintext
if (I’m thread process i)
    do this;
else
    do that;
```
1. Divide the work among the processes/threads
   (a) so each process/thread gets roughly the same amount of work
   (b) and communication is minimized.
2. Arrange for the processes/threads to synchronize.
3. Arrange for communication among processes/threads.

```c
double x[n], y[n];
...
for (i = 0; i < n; i++)
    x[i] += y[i];
```
In a shared memory program, variables can be shared or private

- Implicit communication through shared variables

- A shared memory program consists of multiple threads
  → dynamic/static threads

- Multiple threads can access a shared variable concurrently
  → No determinism
Shared Memory (2)

- **Dynamic threads**
  - Master thread waits for work, forks new threads, and when threads are done, they terminate.
  - Efficient use of resources, but thread creation and termination is time consuming.

- **Static threads**
  - Pool of threads created and are allocated work, but do not terminate until cleanup.
  - Better performance, but potential waste of system resources.
Nondeterminism

... printf ( "Thread %d > my_val = %d\n" , my_rank , my_x ) ;
...

Thread 0 > my_val = 7
Thread 1 > my_val = 19

Thread 1 > my_val = 19
Thread 0 > my_val = 7
Nondeterminism

```c
my_val = Compute_val ( my_rank ) ;
x += my_val ;
```

<table>
<thead>
<tr>
<th>Time</th>
<th>Core 0</th>
<th>Core 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Finish assignment to my_val</td>
<td>In call to Compute_val</td>
</tr>
<tr>
<td>1</td>
<td>Load x = 0 into register</td>
<td>Finish assignment to my_val</td>
</tr>
<tr>
<td>2</td>
<td>Load my_val = 7 into register</td>
<td>Load x = 0 into register</td>
</tr>
<tr>
<td>3</td>
<td>Add my_val = 7 to x</td>
<td>Load my_val = 19 into register</td>
</tr>
<tr>
<td>4</td>
<td>Store x = 7</td>
<td>Add my_val to x</td>
</tr>
<tr>
<td>5</td>
<td>Start other work</td>
<td>Store x = 19</td>
</tr>
</tbody>
</table>
Nondeterminism

- Race condition
- Critical section
- Mutually exclusive
- Mutual exclusion lock (mutex, or simply lock)

```c
my_val = Compute_val ( my_rank ) ;
Lock(&add_my_val_lock ) ;
x += my_val ;
Unlock(&add_my_val_lock ) ;
```
**Mutual exclusion**

- **Mutex lock**
  - Only one thread can enter a critical section
  - Other threads sleep until a lock owner exits the critical section

- **Spinlock**
  - Other threads are spinning until a lock owner exits the critical section

- **Semaphore**
  - Allow multiple threads can enter a critical section

- **Monitor**
  - Providing mutual exclusion at a higher-level
Mutual exclusion (2)

- **Read/Write lock**
  - Multiple readers can concurrently enter a critical section
  - A single writer can enter a critical section without readers

- **Variants of spinlock**
  - Ticket lock
    - Spinners (waiters) have its ticket
    - No starvation
  - MCS lock
    - Cacheline movement is minimized
    - Each spinner spins on a different lock variable to each other
Mutual exclusion (3)

- **Read-Copy-Update**
  - Multiple readers and one writer can enter the critical section without any lock being held
  - Writers should be mutually exclusive to each other
  - Update to a shared variable should follow a rule

- **Transactional memory**
  - Multiple memory updates are treated as a transaction
  - Commit or abort memory updates
Thread Safety

⇣ Thread safe

⇣ A code or a function is safe when multiple threads can safely use it

⇣ strtok() in C is not thread safe

⇣ Its internal buffer is shared between threads because it is static

```c
char* a = "abc def", *token;
token = strtok(a, " ");
// token == "abc"?
token = strtok(NULL, " ");
// token == "def"?
```

Thread 0

```c
char* a = "ghi jkl", *token;
token = strtok(a, " ");
// token == "ghi"?
token = strtok(NULL, " ");
// token == "jkl"?
```

Thread 1

⇣ strtok_r() is thread-safe

⇣ Strtok_r(char* str, char* delim, char** saveptr)

⇣ Saveptr is used for a thread-local buffer
Thread Safety (1)

- `strtok_r()` is thread-safe
  - `Strtok_r(char* str, char* delim, char** saveptr)`
  - `Saveptr` is used for a thread-local buffer

```c
char* a = "abc def", *token;
char* ptr;
token = strtok_r(a, " ", &ptr);
// token == "abc"? yes

char* a = "ghi jkl", *token;
char * ptr;
token = strtok_r(a, " ", &ptr);
// token == "ghi"? yes
```  

Thread 0  Thread 1

- POSIX.1 specifies thread-safe functions
  - E.g., `read()`, `write()`, `printf()`, ...
  - Just do “man 7 pthread” in UNIX shell
Thread Safety (2)

- **Download and test the codes**
Distributed memory

- Each process can access only its private (local) memory

- Application framework for building a program in distributed memory
  - Ex. MPI (message passing interface), Hadoop
  - APIs for sending/receiving messages
  - Running multiple programs at once
    - Ex. mpiexec
char message [100] ;

... 

my_rank = Get_rank ( ) ;
if ( my_rank == 1) {
    sprintf ( message , "Greetings from process 1" ) ;
    Send ( message , MSG_CHAR , 100 , 0 ) ;
}
else if ( my_rank == 0) {
    Receive ( message , MSG_CHAR , 100 , 1 ) ;
    printf ( "Process 0 > Received: %s\n" , message ) ;
}
Distributed memory (2)

- Shared-memory programming easy and appealing to programmers

- Distributed shared memory (DSM)
  - Compiler of operating system provide a transparent view of a shared-memory system upon a distributed memory system
  - Shared memory accesses are translated to sending messages
  - Ex. Treadmarks, single system image, partitioned global address space languages
shared int n = ...;
shared double x[n], y[n];
private int i, my_first_element, my_last_element;
my_first_element = ...;
my_last_element = ...;
/* Initialize x and y */
...
for (i = my_first_element; i <= my_last_element; i++)
    x[i] += y[i];
In distributed memory programs, only process 0 will access *stdin*. In shared memory programs, only the master thread or thread 0 will access *stdin*.

In both distributed memory and shared memory programs all the processes/threads can access *stdout* and *stderr*. 
However, because of the indeterminacy of the order of output to *stdout*, in most cases only a single process/thread will be used for all output to *stdout* other than debugging output.

Debug output should always include the rank or id of the process/thread that’s generating the output.
**Input and Output**

- Only a single process/thread will attempt to access any single file other than *stdin*, *stdout*, or *stderr*.
- So, for example, each process/thread can open its own, private file for reading or writing, but no two processes/threads will open the same file.
PERFORMANCE
**Speedup**

- **Number of cores** = \( p \)
- **Serial run-time** = \( T_{\text{serial}} \)
- **Parallel run-time** = \( T_{\text{parallel}} \)

**Speedup** = \( S = \frac{T_{\text{serial}}}{T_{\text{parallel}}} \)

**Linear speedup** = \( T_{\text{parallel}} = \frac{T_{\text{serial}}}{p} \)
Efficiency of a parallel program

- **Efficiency**
  \[ E = \frac{S}{p} = \frac{T_{\text{serial}}}{T_{\text{parallel}}} = \frac{T_{\text{serial}}}{p \cdot T_{\text{parallel}}} \]

- **Effect of overhead**
  - Spawning multiple threads/processes
  - Message passing overhead

  \[ T_{\text{parallel}} = \frac{T_{\text{serial}}}{p} + T_{\text{overhead}} \]
Speedups and efficiencies of a parallel program

\[ T_{\text{parallel}} = \frac{T_{\text{serial}}}{p} + T_{\text{overhead}} \]

<table>
<thead>
<tr>
<th>( p )</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>8</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S )</td>
<td>1.0</td>
<td>1.9</td>
<td>3.6</td>
<td>6.5</td>
<td>10.8</td>
</tr>
<tr>
<td>( E = \frac{S}{p} )</td>
<td>1.0</td>
<td>0.95</td>
<td>0.90</td>
<td>0.81</td>
<td>0.68</td>
</tr>
</tbody>
</table>

- \( T_{\text{overhead}} \)
  - Usually proportional to the number of process/threads
Speedups and efficiencies of parallel program on different problem sizes

\[ T_{parallel} = \frac{T_{serial}}{p} + T_{overhead} \]

<table>
<thead>
<tr>
<th></th>
<th>( p )</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>8</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half</td>
<td>( S )</td>
<td>1.0</td>
<td>1.9</td>
<td>3.1</td>
<td>4.8</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>( E )</td>
<td>1.0</td>
<td>0.95</td>
<td>0.78</td>
<td>0.60</td>
<td>0.39</td>
</tr>
<tr>
<td>Original</td>
<td>( S )</td>
<td>1.0</td>
<td>1.9</td>
<td>3.6</td>
<td>6.5</td>
<td>10.8</td>
</tr>
<tr>
<td></td>
<td>( E )</td>
<td>1.0</td>
<td>0.95</td>
<td>0.90</td>
<td>0.81</td>
<td>0.68</td>
</tr>
<tr>
<td>Double</td>
<td>( S )</td>
<td>1.0</td>
<td>1.9</td>
<td>3.9</td>
<td>7.5</td>
<td>14.2</td>
</tr>
<tr>
<td></td>
<td>( E )</td>
<td>1.0</td>
<td>0.95</td>
<td>0.98</td>
<td>0.94</td>
<td>0.89</td>
</tr>
</tbody>
</table>

- With the same \( T_{overhead} \), increasing the size of problem decreases the portion of \( T_{overhead} \)
Speedup

![Graph showing speedup for different process sizes. The graph compares speedup against the number of processes for different data set sizes: Half size, Original, and Double size. The lines show a linear relationship.]
Efficiency

The graph shows the efficiency of processes over different sizes and numbers of processes. The x-axis represents the number of processes, while the y-axis represents the efficiency. Three lines are depicted, each representing a different size: Half size, Original, and Double size. As the number of processes increases, the efficiency decreases for all sizes, with the Half size showing the least decrease, followed by the Original, and then the Double size showing the most decrease.
Amdahl’s Law

- The possible speedup is going to be very limited — regardless of the number of cores available.

\[ S(n) = \frac{T(1)}{T(n)} = \frac{T(1)}{T(1)(B + \frac{1}{n}(1 - B))} = \frac{1}{B + \frac{1}{n}(1 - B)} \]

- \( n \in \mathbb{N} \): # of threads
- \( B \in [0, 1] \): Fraction of serial part
We can parallelize 90% of a serial program.
Parallelization is “perfect” regardless of the number of cores \( p \) we use.

\[ T_{\text{serial}} = 20 \text{ seconds} \]

Runtime of parallelizable part is

\[ 0.9 \times T_{\text{serial}} / p = 18 / p \]
Example (cont.)

- Runtime of “unparallelizable” part is

\[ 0.1 \times T_{\text{serial}} = 2 \]

- Overall parallel run-time is

\[ T_{\text{parallel}} = 0.9 \times T_{\text{serial}} / p + 0.1 \times T_{\text{serial}} = 18 / p + 2 \]

- Speed up is

\[ S = \frac{T_{\text{serial}}}{0.9 \times T_{\text{serial}} / p + 0.1 \times T_{\text{serial}}} = \frac{20}{18 / p + 2} \]
Scalability

- In general, a problem is **scalable** if it can handle ever increasing problem sizes.
- If we increase the number of processes/threads and keep the efficiency fixed without increasing problem size, the problem is **strongly scalable**.
- If we keep the efficiency fixed by increasing the problem size at the same rate as we increase the number of processes/threads, the problem is **weakly scalable**.
Scalability issues in Commodity OS

[S. Boyd-Wickizer, et. al., OSDI 2010]
Taking Timings

- What is time?
- Start to finish?
- A program segment of interest?
- CPU time?
- Wall clock time?
Taking Timings

```c
double start, finish;

start = Get_current_time();
/* Code that we want to time */

finish = Get_current_time();
printf("The elapsed time = %e seconds\n", finish - start);
```

- MPI_Wtime
- omp_get_wtime
- theoretical function
Taking Timings

shared double global_elapsed;
private double my_start, my_finish, my_elapsed;

/* Synchronize all processes/threads */
Barrier();
my_start = Get_current_time();

/* Code that we want to time */

my_finish = Get_current_time();
my_elapsed = my_finish - my_start;

/* Find the max across all processes/threads */
global_elapsed = Global_max(my_elapsed);
if (my_rank == 0)
    printf("The elapsed time = %e seconds\n", global_elapsed);
PARALLEL PROGRAM DESIGN
Foster’s methodology

1. **Partitioning**: divide the computation to be performed and the data operated on by the computation into small tasks.

   The focus here should be on identifying tasks that can be executed in parallel.

2. **Communication**: determine what communication needs to be carried out among the identified in the previous step.
Foster’s methodology

3. **Agglomeration or aggregation**: combine tasks and communications identified in the first step into larger tasks.

For example, if task A must be executed before task B can be executed, it may make sense to aggregate them into a single composite task.
Foster’s methodology

4. **Mapping**: assign the composite tasks identified in the previous step to processes/threads.

This should be done so that communication is minimized, and each process/thread gets roughly the same amount of work.
Example - histogram

- 1.3, 2.9, 0.4, 0.3, 1.3, 4.4, 1.7, 0.4, 3.2, 0.3, 4.9, 2.4, 3.1, 4.4, 3.9, 0.4, 4.2, 4.5, 4.9, 0.9
1. The number of measurements: `data_count`
2. An array of `data_count` floats: `data`
3. The number of bins: `bin_count`
4. `bin_maxes`: an array of `bin_count` floats
   Ex. `bin_maxes = [1, 2, 3, 4, 5]`
5. `bin_counts`: an array of `bin_count` ints
   Ex. `bin_counts = [6, 3, 2, 3, 6]`

```
Find_bin ... data[i-1] data[i] data[i+1] ...
```

```
Increment bin_counts ... bin_counts[b-1]++ bin_counts[b]++ ...
```
First two stages of Foster’s Methodology

Find_bin

| data[i-1] | data[i] | data[i+1] |

Increment

| bin_counts[b-1]++ | bin_counts[b]++ |

- **Partition data array only**
  - Core 0 works on data[0] ~ data[n/p – 1]
  - Core 1 works on data[n/p] ~ data[2n/p – 1]
  - ...
  - bin_counts is shared
  - Enormous communication for each update of bin_counts
  - We have to aggregate the task for updating bin_counts to each thread
Partition data array and bin_counts array

- Core 0 works on \( \text{data}[0] \sim \text{data}[n/p - 1] \)
- ... 
- Each thread has private \text{loc_bin_cts} 
- Communication is only to merge multiple \text{loc_bin_cts} variables
Adding the local arrays
Concluding Remarks (1)

- **Parallel software**
  - We focus on software for homogeneous MIMD systems, consisting of a single program that obtains parallelism by branching.
  - SPMD programs.

- **Shared/Distributed memory system**
  - Communication/synchronization
  - Nondeterminism

- **Input and Output**
  - Be careful of using stdin/out/err and file accesses
Concluding Remarks (2)

- **Performance**
  - Speedup
  - Efficiency
  - Amdahl’s law
  - Scalability

- **Parallel Program Design**
  - Foster’s methodology