HW3: Shared-Memory Sample Sort

Course: CMSC751/ENEE759, Spring 2009
Title: Shared-Memory Sample Sort
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Date Due: March 24th, 2009
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1 Assignment Goal

The goal of this assignment is to provide a randomized sorting algorithm that runs efficiently on XMT. While you are allowed some flexibility as to what serial sorting algorithms to use for different steps of the parallel algorithm, you should try to find and select the most efficient one for each case. The Sample Sort algorithm follows a "decomposition first" pattern and is widely used on multiprocessor architectures. Being a randomized algorithm, its running time depends on the output of a random number generator. Sample Sort performs well on very large arrays, with high probability.

In this assignment, we propose implementing a variation of the Sample Sort algorithm that performs well on shared memory parallel architectures such as XMT.

2 Problem Statement

The Shared Memory Sample Sort algorithm is an implementation of Sample Sort for shared memory machines. The idea behind Sample Sort is to find a set of \( p - 1 \) elements from the array, called splitters, which partition the \( n \) input elements into \( p \) groups \( \text{set}_0 \ldots \text{set}_{p-1} \). In particular, every element in \( \text{set}_i \) is smaller than every element in \( \text{set}_{i+1} \). The partitioned sets are then sorted independently.

The input is an unsorted array \( A \). The output is returned in array \( \text{Result} \). Let \( p \) be the number of processors. We will assume, without loss of generality, that \( N \) is divisible by \( p \). An overview of the Shared Memory Sample Sort algorithm is as follows:

**Step 1.** In parallel, a set \( S \) of \( s \times p \) random elements from the original array \( A \) is collected, where \( p \) is the number of TCUs available and \( s \) is called the oversampling ratio. Sort the array \( S \), using an algorithm that performs well for the size of \( S \). Select a set of \( p - 1 \) evenly spaced elements from it into \( S' \): 

\[
S' = \{S[x], S[2x], \ldots, S[(p-1) \times s]\}
\]

These elements are the splitters that are used below to partition the elements of \( A \) into \( p \) sets (or partitions) \( \text{set}_i \), \( 0 \leq i < p \). The sets are

\[
\text{set}_0 = \{A[i] \mid A[i] < S'[0]\}, \quad \text{set}_1 = \{A[i] \mid S'[0] \leq A[i] < S'[1]\}, \ldots, \quad \text{set}_{p-1} = \{A[i] \mid S'[(p-1)] \leq A[i]\}.
\]

**Step 2.** Consider the input array \( A \) divided into \( p \) subarrays, \( B_0 = A[0, \ldots, (N/p) - 1], B_1 = A[N/p, \ldots, 2(N/p) - 1] \) etc. The \( i \)th TCU iterates through subarray \( B_i \) and for each element executes a binary search on the array of splitters \( S' \), for a total of \( N/p \) binary searches per TCU. The following quantities are computed:
• $c_{ij}$ - the number of elements from $B_i$ that belong in partition set $j$. The $c_{ij}$ makes up the matrix $C$ as in figure 1.

• partition $k$ - the partition (i.e. the set) in which element $A[k]$ belongs. Each element is tagged with such an index.

• serial $k$ - the number of elements in $B_i$ that belong in set partition $k$ but are located before $A[k]$ in $B_i$.

For example, if $B_0 = [105, 101, 99, 205, 75, 14]$ and we have $S' = [100, 150, \ldots]$ as splitters, we will have $c_{0,0} = 3, c_{0,1} = 2$ etc., partition $0 = 1$, partition $2 = 0$ etc. and serial $0 = 0, serial_1 = 1, serial_5 = 2$.

**Step 3.** Compute prefix-sums $ps_{i,j}$ for each column of the matrix $C$. For example, $ps_{0,j}, ps_{1,j}, \ldots, ps_{p-1,j}$ are the prefix-sums of $c_{0,j}, c_{1,j}, \ldots, c_{p-1,j}$.

Also compute the sum of column $i$, which is stored in $sum_i$. Compute the prefix sums of the $sum_1, \ldots, sum_p$ into global$_{ps_0}, \ldots, global_{ps_p}$ and the total sum of $sum_i$ in global$_{ps_p}$. This definition of global$_{ps}$ turns out to be a programming convenience.

**Step 4.** Each TCU $i$ computes: for each element $A[j]$ in segment $B_i$, $i \cdot \frac{N}{p} \leq j < (i+1)\frac{N}{p}$:

$$pos_j = global_{ps_{\text{partition}_j}} + ps_{i,\text{partition}_j} + \text{serial}_j$$


**Step 5.** TCU $i$ executes a (serial) sorting algorithm on the elements of set $i$, which are now stored in $\text{Result}[\text{global}_{ps_i}, \ldots, \text{global}_{ps_{i+1}} - 1]$.

At the end of Step 5, the elements of $A$ are stored in sorted order in $\text{Result}$.
3 Hints and Remarks

Sorting algorithms  The Sample Sort algorithm uses two other sorting algorithms as building blocks:

- Sorting the array $S$ of size $s \times p$. Any serial or parallel sorting algorithm can be used. Note that for the "interesting" values of $N$ (i.e. $N \gg p$), the size of $S$ is much smaller than the size of the original problem. An algorithm with best overall performance is expected.
- Serially sorting partitions of $Result$ by each TCU. Any serial sorting algorithm can be used. Remember to follow the restrictions imposed on spawn blocks, such as not allowing function calls, and avoid concurrent reads or writes to memory.

Oversampling ratio  The oversampling ratio $s$ influences the quality of the partitioning process. When $s$ is large, the partitioning is more balanced with high probability, and the algorithm performs better. However, this means more time is spent in sampling and sorting $S$. The optimum value for $s$ depends on the size of the problem. We will use a default value of $s = 8$ for the inputs provided.

Random numbers for sampling  Step 1 requires using a random number generator. Such a library function is not yet implemented on XMT. We have provided you with a pre-generated sequence of random numbers as an array in the input. The number of random values in the sequence is provided as part of the input. The numbers are positive integers in the range $0..1,000,000$. You need to normalize these values to the range that you need in your program. Use a global index into this array and increment it (avoiding concurrent reads or writes) each time a random number is requested, possibly wrapping around if you run out of random numbers.

Number of TCUs  Although the number of TCUs on a given architecture is fixed (e.g. 1024 or 64), for the purpose of this assignment we can scale down this number to allow easier testing and debugging. The number of available TCUs will be provided as part of the input for each dataset.

4 Assignment

1. Parallel Sort:  Write a parallel XMTC program ssort.p.c that implements the Shared Memory Sample Sort algorithm. This implementation should be as fast as possible.

2. Serial Sort:  Write a serial XMTC program ssort.s.c that implements a serial sorting algorithm. This implementation will be used to for speedup comparison. You can use one of the serial sorting algorithms implemented as part of sample sort, or you can write a different sorting algorithm.

4.1 Setting up the environment

The header files and the binary files can be downloaded from /opt/xmt/class/xmtdatal/. To get the data files, log in to your account in the class server and copy the ssort.tgz file from directory using the following commands:

```bash
$ cp /opt/xmt/class/xmtdatal/ssort.tgz ~
$ tar xzvf ssort.tgz
```

This will create the directory ssort with following folders: data, src, and doc. Data files are available in data directory. Put your c files in src, and txt files to doc.
4.2 Input Format

The input is provided as an array of integers $A$.

<table>
<thead>
<tr>
<th>#define N</th>
<th>The number of elements to sort.</th>
</tr>
</thead>
<tbody>
<tr>
<td>int s</td>
<td>The oversampling ratio.</td>
</tr>
<tr>
<td>#define NTCU</td>
<td>The number of TCUs to be used for sorting.</td>
</tr>
<tr>
<td>#define NRAND</td>
<td>The number of random values in the RANDOM array.</td>
</tr>
<tr>
<td>int RANDOM[NRAND]</td>
<td>An array with pregenerated random integers.</td>
</tr>
<tr>
<td>int result[N]</td>
<td>To store the result of the sorting.</td>
</tr>
</tbody>
</table>

You can declare any number of global arrays and variables in your program as needed. The number of elements in the arrays ($n$) is declared as a constant in each dataset, and you can use it to declare auxiliary arrays. For example, this is valid XMTC code:

```c
#define N 16384

int temp1[16384];
int temp2[2*N];
int pointer;

int main() {
     //...
}
```

4.3 Data sets

Run all your programs (serial and parallel) using the data files given in the following table. You can directly include the header file into your XMTC code with `#include` or you can include the header file with the compiler option `-include`.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>N</th>
<th>NTCU</th>
<th>Header File</th>
<th>Binary file</th>
</tr>
</thead>
<tbody>
<tr>
<td>d1</td>
<td>256</td>
<td>8</td>
<td>data/d1/ssort.h</td>
<td>data/d1/ssort.xbo</td>
</tr>
<tr>
<td>d2</td>
<td>4096</td>
<td>8</td>
<td>data/d2/ssort.h</td>
<td>data/d2/ssort.xbo</td>
</tr>
<tr>
<td>d3</td>
<td>128k</td>
<td>64</td>
<td>data/d3/ssort.h</td>
<td>data/d3/ssort.xbo</td>
</tr>
</tbody>
</table>

4.4 Compiling and Executing

You can compile the parallel program using the following command line for the small dataset (d1):

```bash
> xmtcc -include ../data/d1/ssort.h ../data/d1/ssort.xbo ssort.p.c -o ssort.p
```

If the program compiles correctly a file called `ssort.p.b` will be created. This is the binary executable you will run on the FPGA using the following command:

```bash
> xmtfpga ssort.p.b
```

5 Output

The array has to be sorted in increasing order. The array `result` should hold the array of sorted values.

Prepare and fill the following table: Create a text file named `table.txt` in `doc`. Remove any `printf` statements from your code while taking these measurements. `Printf` statements increase the clock count. Therefore the measurements with printf statements may not reflect the actual time and work done.
<table>
<thead>
<tr>
<th>Dataset</th>
<th>d1</th>
<th>d2</th>
<th>d3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parallel sort clock cycles</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Serial sort clock cycles</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note that a part of your grading criteria is the performance of your parallel implementation on the largest dataset (d3). Therefore you should try to obtain the fastest running parallel program. As a guideline, for the larger dataset (d3) our Serial Sort runs in 45526102 cycles, and our Parallel Sample runs in 9047152 cycles (speedup $\sim 5x$) on the FPGA computer.

5.1 Submission

The use of the make utility for submission `make submit` is required. Make sure that you have the correct files at correct locations (`src` and `doc` directories) using the make `submitcheck` command. Run following commands to submit the assignment:

```bash
$ make submitcheck
$ make submit
```

5.2 Discussion about Serial Sorting Algorithms

In this assignment you need a serial sorting algorithm in three different places. First when you implement the serial sorting itself to compare against your implementation, but also within the sample sort algorithm, first to sort the array of samples $S$ and later to sort in parallel the $p$ segments. So choosing the right serial sorting algorithm is very important. The discussion below should guide you and limit your search space when looking for the best serial algorithms to use with sample sort.

Table 1: Table of cycle counts for different serial sorting algorithms and sample sort using different sorting algorithms

<table>
<thead>
<tr>
<th>Dataset</th>
<th>d1</th>
<th>d2</th>
<th>d3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serial(QS)</td>
<td>50302</td>
<td>1002756</td>
<td>45526102</td>
</tr>
<tr>
<td>Serial(HS)</td>
<td>64376</td>
<td>1562200</td>
<td>103129058</td>
</tr>
<tr>
<td>Serial(BS)</td>
<td>327350</td>
<td>96523199</td>
<td>timeout</td>
</tr>
<tr>
<td>Serial(BS+check)</td>
<td>340158</td>
<td>100349982</td>
<td>timeout</td>
</tr>
<tr>
<td>Sample Sort (QS/HS)</td>
<td>59011</td>
<td>1501593</td>
<td>9047152</td>
</tr>
<tr>
<td>Sample Sort (HS/HS)</td>
<td>59819</td>
<td>1502359</td>
<td>9101561</td>
</tr>
<tr>
<td>Sample Sort (QS/BS)</td>
<td>150381</td>
<td>83490620</td>
<td>timeout</td>
</tr>
</tbody>
</table>

In Table 1 the performance of four serial sorting algorithms is compared as well as the performance of sample sort using some combinations of these algorithms. The serial algorithms are `quicksort (QS)`, `heapsort (HS)`, `bubble sort (BS)` and `bubble sort with termination check (BS+check)`\(^1\). The notation “Sample Sort(XX/YY)” indicates the parallel sample sort algorithm using the serial sorting algorithm XX in Step 1 to sort array $S$ and the serial sorting algorithm YY in Step 5.

The Table shows that the fastest serial algorithm of the ones compared is quicksort, heapsort comes second, and bubble sort is too slow to get a cycle count for the largest dataset. Quicksort however is a recursive algorithm, naturally implemented using recursive function calls. For that reason it was not used for Step 5 (the QS/QS configuration was not implemented) since function calls are currently not supported in parallel code. Students have been able to implement a non-recursive version of quicksort to use in Step 5 which gave improved performance.

\(^1\)The algorithm checks after each of the $N$ passes of the input array $A[N]$ if there were any swaps. If not it terminates earlier.