Parallel Sorting Algorithms

1. Sorting in C and C++
   - using `qsort` in C
   - using STL `sort` in C++

2. Bucket Sort for Distributed Memory
   - bucket sort in parallel
   - communication versus computation

3. Quicksort for Shared Memory
   - partitioning numbers
   - quicksort with OpenMP
   - parallel sort with Intel TBB

MCS 572 Lecture 12
Introduction to Supercomputing
Jan Verschelde, 19 September 2016
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using `qsort`

C provides an implementation of quicksort. The prototype is

```c
void qsort ( void *base, size_t count, size_t size,
            int (*compar)(const void *element1,
                           const void *element2) );
```

`qsort` sorts an array whose first element is pointed to by `base` and contains `count` elements, of the given size.

The function `compar` returns

-1 if `element1 < element2`,
0 if `element1 = element2`,
+1 if `element1 > element2`.

We will apply `qsort` to sort a random sequence of doubles.
void random_numbers ( int n, double a[n] )
{
    int i;
    for(i=0; i<n; i++)
        a[i] = ((double) rand())/RAND_MAX;
}

void write_numbers ( int n, double a[n] )
{
    int i;
    for(i=0; i<n; i++) printf("%.15e\n", a[i]);
}
using `qsort`

```c
int compare ( const void *e1, const void *e2 )
{
    double *i1 = (double*)e1;
    double *i2 = (double*)e2;
    return ((*i1 < *i2) ? -1 : (*i1 > *i2) ? +1 : 0);
}
```

in the function `main()`:

```c
double *a;
a = (double*)calloc(n,sizeof(double));
random_numbers(n,a);
qsort((void*)a,(size_t)n,sizeof(double),compare);
```
We use the command line to enter the dimension and to toggle off the output.

To measure the CPU time for sorting:

```c
clock_t tstart, tstop;
tstart = clock();
qsort((void*)a, (size_t)n, sizeof(double), compare);
tstop = clock();
printf("time elapsed : \%.4lf seconds\n",
       (tstop - tstart)/((double) CLOCKS_PER_SEC));
```
Timing qsort on 3.47GHz Intel Xeon

$ time /tmp/time_qsort 1000000 0
  time elapsed : 0.2100 seconds
  real       0m0.231s
  user       0m0.225s
  sys        0m0.006s

$ time /tmp/time_qsort 10000000 0
  time elapsed : 2.5700 seconds
  real       0m2.683s
  user       0m2.650s
  sys        0m0.033s

$ time /tmp/time_qsort 100000000 0
  time elapsed : 29.5600 seconds
  real       0m30.641s
  user       0m30.409s
  sys        0m0.226s

Observe: $O(n \log_2(n))$ is almost linear in $n$. 
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using the STL container `vector`

```cpp
#include <vector>
using namespace std;

vector<double> random_vector ( int n );  // returns a vector of n random doubles

vector<double> random_vector ( int n )
{
    vector<double> v;
    for(int i=0; i<n; i++)
    {
        double r = (double) rand();
        r = r/RAND_MAX;
        v.push_back(r);
    }
    return v;
}
```
writing STL vectors

#include <iostream>
#include <iomanip>
#include <vector>
using namespace std;

void write_vector ( vector<double> v );
// writes the vector v

void write_vector ( vector<double> v )
{
    for(int i=0; i<v.size(); i++)
        cout << scientific
            << setprecision(15)
            << v[i] << endl;
}
using the STL sort

#include <vector>
#include <algorithm>
using namespace std;

struct less_than // defines "<"
{
    bool operator()(const double& a,
                    const double& b)
    {
        return (a < b);
    }
};

in the main program:

sort(v.begin(),v.end(),less_than());
timing STL sort on 3.47GHz Intel Xeon

$ time /tmp/time_stl_sort 1000000 0
time elapsed : 0.36 seconds
real 0m0.376s
user 0m0.371s
sys 0m0.004s
$ time /tmp/time_stl_sort 10000000 0
time elapsed : 4.09 seconds
real 0m4.309s
user 0m4.275s
sys 0m0.033s
$ time /tmp/time_stl_sort 100000000 0
time elapsed : 46.5 seconds
real 0m48.610s
user 0m48.336s
sys 0m0.267s

Different distributions may cause timings to fluctuate.
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bucket sort

Given are \( n \) numbers, suppose all are in \([0, 1]\).

The algorithm using \( p \) buckets proceeds in two steps:

- Partition numbers \( x \) into \( p \) buckets:
  \[
  x \in \left[ \frac{i}{p}, \frac{i + 1}{p} \right] \Rightarrow x \in (i + 1)\text{th bucket}.
  \]
- Sort all \( p \) buckets.

The cost to partition the numbers into \( p \) buckets is \( O(n \log_2(p)) \).
Note: radix sort uses most significant bits to partition.

In the best case: every bucket contains \( n/p \) numbers.
The cost of Quicksort is \( O(n/p \log_2(n/p)) \) per bucket.
Sorting \( p \) buckets takes \( O(n \log_2(n/p)) \).
The total cost is \( O(n(\log_2(p) + \log_2(n/p))) \).
parallel bucket sort

On \( p \) processors, all nodes sort:

1. Root node distributes numbers: processor \( i \) gets \( i \)th bucket.
2. Processor \( i \) sorts \( i \)th bucket.
3. Root node collects sorted buckets from processors.

Is it worth it? Recall: serial cost is \( n(\log_2(p) + \log_2(n/p)) \).

Cost of parallel algorithm:
- \( n \log_2(p) \) to place numbers into buckets,
- \( n/p \log_2(n/p) \) to sort buckets.

speedup
\[
\frac{n(\log_2(p) + \log_2(n/p))}{n(\log_2(p) + \log_2(n/p)/p)} = \frac{1 + L}{1 + L/p} = \frac{1 + L}{(p + L)/p} = \frac{p}{p + L}(1 + L), \quad L = \frac{\log_2(n/p)}{\log_2(p)}.
\]
comparing to quicksort

\[
\text{speedup} = \frac{n \log_2(n)}{n \left(\log_2(p) + n/p \log_2(n/p)\right)}
\]

\[
= \frac{\log_2(n)}{\log_2(p) + 1/p(\log_2(n) - \log_2(p))}
\]

\[
= \frac{1/p(\log_2(n) + (1 - 1/p) \log_2(p))}{\log_2(n)}
\]

Example: \( n = 2^{20}, \log_2(n) = 20, \ p = 2^2, \log_2(p) = 2, \)

\[
\text{speedup} = \frac{20}{1/4(20) + (1 - 1/4)2}
\]

\[
= \frac{20}{5 + 3/2} = \frac{40}{13} \approx 3.08.
\]
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communication and computation

The scatter of \( n \) data elements costs \( t_{\text{start up}} + nt_{\text{data}} \), where \( t_{\text{data}} \) is the cost of sending 1 data element.

For distributing and collecting of all buckets, the total communication time is \( 2p \left( t_{\text{start up}} + \frac{n}{p} t_{\text{data}} \right) \).

The computation/communication ratio is

\[
\frac{(n \log_2(p) + n/p \log_2(n/p)) t_{\text{compare}}}{2p \left( t_{\text{start up}} + \frac{n}{p} t_{\text{data}} \right)}
\]

where \( t_{\text{compare}} \) is the cost for one comparison.
the computation/communication ratio

The computation/communication ratio is

\[
\frac{(n \log_2(p) + n/p \log_2(n/p)) t_{\text{compare}}}{2p \left(t_{\text{start up}} + \frac{n}{p} t_{\text{data}}\right)}
\]

where \( t_{\text{compare}} \) is the cost for one comparison.

We view this ratio for \( n \gg p \), for fixed \( p \), so:

\[
\frac{n}{p} \log_2 \left( \frac{n}{p} \right) = \frac{n}{p} (\log_2(n) - \log_2(p)) \approx \frac{n}{p} \log_2(n).
\]

The ratio then becomes

\[
\frac{n}{p} \log_2(n) t_{\text{compare}} \gg 2nt_{\text{data}}.
\]

Thus \( \log_2(n) \) must be sufficiently high...
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a recursive algorithm

```c
void quicksort ( double *v, int start, int end ) {
    if(start < end) {
        int pivot;
        partition(v,start,end,&pivot);
        quicksort(v,start,pivot-1);
        quicksort(v,pivot+1,end);
    }
}
```

where `partition` has the prototype:

```c
void partition
    ( double *v, int lower, int upper, int *pivot );

/* precondition: upper - lower > 0
 * takes v[lower] as pivot and interchanges elements:
 * v[i] <= v[pivot] for all i < pivot, and
 * v[i] > v[pivot] for all i > pivot,
 * where lower <= pivot <= upper. */
```
void partition
    ( double *v, int lower, int upper, int *pivot )
{
    double x = v[lower];
    int up = lower + 1; /* index will go up */
    int down = upper;  /* index will go down */
    while(up < down)
    {
        while((up < down) && (v[up] <= x)) up++;
        while((up < down) && (v[down] > x)) down--;
        if(up == down) break;
        double tmp = v[up];
        v[up] = v[down]; v[down] = tmp;
    }
    if(v[up] > x) up--;
    v[lower] = v[up]; v[up] = x;
    *pivot = up;
}
partition and \texttt{qsort} in \texttt{main}()

\begin{verbatim}
int lower = 0;
int upper = n-1;
int pivot = 0;
if(n > 1) partition(v,lower,upper,&pivot);

if(pivot != 0)
    \texttt{qsort}((void*)v,(size_t)pivot,
                sizeof(double),compare);

if(pivot != n)
    \texttt{qsort}((void*)&v[pivot+1],(size_t)(n-pivot-1),
                sizeof(double),compare);
\end{verbatim}
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a parallel region in `main()`

```c
omp_set_num_threads(2);
#pragma omp parallel
{
    if(pivot != 0)
        qsort((void*)v,(size_t)pivot,
              sizeof(double),compare);
    if(pivot != n)
        qsort((void*)&v[pivot+1],(size_t)(n-pivot-1),
              sizeof(double),compare);
}
```
on dual core Mac OS X at 2.26 GHz

$ time /tmp/time_qsort 10000000 0
time elapsed : 4.0575 seconds

real 0m4.299s
user 0m4.229s
sys 0m0.068s

$ time /tmp/part_qsort_omp 10000000 0
pivot = 4721964
-> sorting the first half : 4721964 numbers
-> sorting the second half : 5278035 numbers

real 0m3.794s
user 0m7.117s
sys 0m0.066s

Speed up: 4.299/3.794 = 1.133, or 13.3% faster with one extra core.
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using `parallel_sort` of the Intel TBB

At the top of the program, add the lines

```cpp
#include "tbb/parallel_sort.h"

using namespace tbb;
```

To sort a number of random doubles:

```cpp
int n;
double *v;
v = (double*)calloc(n,sizeof(double));
random_numbers(n,v);
parallel_sort(v, v+n);
```
an interactive test run

```
$ /tmp/tbb_sort 4 1
4 random numbers:
3.696845319912231e-01
7.545582678888730e-01
6.707372915329120e-01
3.402865237278335e-01
the sorted numbers:
3.402865237278335e-01
3.696845319912231e-01
6.707372915329120e-01
7.545582678888730e-01
$```

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timing parallel runs

$ time /tmp/tbb_sort 10000000 0

real 0m0.479s
user 0m4.605s
sys 0m0.168s

$ time /tmp/tbb_sort 100000000 0

real 0m4.734s
user 0m51.063s
sys 0m0.386s

$ time /tmp/tbb_sort 1000000000 0

real 0m47.400s
user 9m32.713s
sys 0m2.073s

$
recommended reading

- Edgar Solomonik and Laxmikant V. Kale: **Highly Scalable Parallel Sorting.** In the proceedings of the IEEE International Parallel and Distributed Processing Symposium (IPDPS), 2010.

- Mirko Rahn, Peter Sanders, and Johannes Singler: **Scalable Distributed-Memory External Sorting.** In the proceedings of the 26th IEEE International Conference on Data Engineering (ICDE), pages 685-688, IEEE, 2010.

- Davide Pasetto and Albert Akhriev: **A Comparative Study of Parallel Sort Algorithms.** In SPLASH’11, the proceedings of the ACM international conference companion on object oriented programming systems languages and applications, pages 203-204, ACM 2011.
Summary + Exercises

In the book of Wilkinson and Allen, bucket sort is described in §4.2.1 and chapter 10 is entirely devoted to sorting algorithms.

Exercises:

1. Consider the fan out scatter and fan in gather operations and investigate how these operations will reduce the communication cost and improve the computation/communication ratio in bucket sort of $n$ numbers on $p$ processors.

2. Instead of OpenMP, use Pthreads to run Quicksort on two cores.

3. Instead of OpenMP, use the Intel Threading Building Blocks to run Quicksort on two cores.