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BITONIC SORT ON ULTRACOMPUTERS

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Bitonic sort on Ultracomputers*)

by

L.G.L.T. Meertens

ABSTRACT

Ultracomputers are assemblages of processors that are able to operate concurrently and can exchange data through communication lines in, say, one cycle of operation.

Batcher's *bitonic sort* is a sorting network, capable of sorting n inputs in $\Theta((\log n)^2)$ stages. When adapted to conventional computers, it gives rise to an algorithm that runs in time $\Theta(n(\log n)^2)$.

This report describes the algorithm adapted to ultracomputers. The resulting algorithm will take time $\Theta((\log N)^2)$ for ultracomputers of "size" N. The implicit constant factor is low, so that even for moderate values of N the ultracomputer architecture performs faster than the $\Theta(N \log N)$ time conventional architecture can achieve.

KEY WORDS & PHRASES: *computational complexity, sorting networks, parallelism, ultracomputers, bitonic sort.*

*) This research has been done while the author was visiting the Courant Institute of Mathematical Sciences, New York University, New York. It has been published there as Ultracomputer Note #1. This report will be submitted for publication elsewhere.

1. INTRODUCTION

Ultracomputers [1] are assemblages of processors that are able to operate concurrently and can exchange data through communication lines in, say, one cycle of operation.

Batcher's *bitonic sort* (cf. [2], pp.232 ff) is a sorting network, capable of sorting n inputs in $\Theta((\log n)^2)$ stages. When adapted to conventional computers, it gives rise to an algorithm that runs in time $\Theta(n(\log n)^2)$. The method can also be adapted to ultracomputers to exploit their high degree of parallelism. The resulting algorithm will take time $\Theta((\log N)^2)$ for ultracomputers of "size" N. The implicit constant factor is low, so that even for moderate values of N the ultracomputer architecture performs faster than the $\Theta(N \log N)$ time conventional architecture can achieve.

The purpose of this note is to describe the adapted algorithm. After some preliminaries a first version of the algorithm is given whose correctness is easily shown. Next, this algorithm is transformed to make it suitable for an ultracomputer.

2. PRELIMINARIES

<u>DEFINITION</u>. A sequence $s_0,\ldots,s_{n-1}$ of elements from a totally ordered set is *bitonic* if there exist i and j, $0 \le i \le j \le n-1$, such that either

$$s_i \le s_{i+1} \le\ldots\le s_j \quad \text{and} \quad s_j \ge s_{j+1} \ge\ldots\ge s_{n-1} \ge s_0 \ge s_1 \ge\ldots\ge s_i,$$

or

$$s_i \ge s_{i+1} \ge\ldots\ge s_j \quad \text{and} \quad s_j \le s_{j+1} \le\ldots\le s_{n-1} \le s_0 \le s_1 \le\ldots\le s_i.$$

(If the sequence is made into a cycle by connecting the rear back to the front, this means that both ways of going from s_i to s_j give an ordered "run".) Note that a sequence of length ≤ 3 is always bitonic.

Bitonic sort hinges on the following

<u>LEMMA 1</u>. *Let* $s_0,\ldots,s_{2n-1}$ *be bitonic. For* $i = 0,\ldots,n-1$, *interchange* s_i *and* s_{n+i} *if* $s_{n+i} < s_i$. *Then for the resulting sequence, both* $s_0,\ldots,s_{n-1}$ *and*

$s_n, \ldots, s_{2n-1}$ *are bitonic. Moreover, each of the elements* $s_0, \ldots, s_{n-1}$ *is less than or equal to each of the elements* $s_n, \ldots, s_{2n-1}$.

PROOF. See BATCHER [3] or STONE [4]. (The proofs given are rather informal. A more formal proof would be elementary but not very enlightening; it would proceed by distinguishing a number of cases.) $\square$

The elements to be sorted are stored in an array a[0:N-1], where $N = 2^D$ for some integer D. The indices of the array will often be written as bit-strings (binary numbers) $b_{D-1}b_{D-2}\ldots b_0$, corresponding to the integer $b_{D-1}2^{D-1}+\ldots+b_0 2^0$. The notation $b_{H:L}$ denotes the substring $b_H b_{H-1}\ldots b_L$. (Note that the subscript runs from high to low; in order to minimize confusion, capital letters will be used for such subscripts.)

DEFINITION. Ω stands for a mapping from the set of substrings $b_{H:L}$ into the set of order relations $\le$ and $\ge$, satisfying $\Omega(b_{H:H+1})$ is $\le$ and $\Omega(b_{H:L+1}0) \neq \Omega(b_{H:L+1}1)$. One possible solution is given by

$$\Omega(b_{H:L}) \text{ is } \le \text{ if } b_H \oplus b_{H-1} \oplus \ldots \oplus b_L = 0,$$

$$\Omega(b_{H:L}) \text{ is } \ge \text{ if } b_H \oplus b_{H-1} \oplus \ldots \oplus b_L = 1.$$

The symbol $\oplus$ stands for the "logical sum" or "exclusive or", so the summation determines the parity of $b_{H:L}$. A simpler solution is given by: $\Omega(b_{H:L+1}0)$ is $\le$, $\Omega(b_{H:L+1}1)$ is $\ge$. (By convention, $\Omega(b_{H:H+1})$ is $\le$ in either case.)

The assertions of the correctness proof will use three predicates, defined below. Let the array a be (conceptually) divided into 2^{D-P} segments of 2^P elements each. The indices of the elements of a given segment are precisely those which have a common initial bitstring $b_{D-1:P}$.

DEFINITION. Ordered (P) stands for: within each segment the elements are sorted in $\Omega(b_{D-1:P})$-order.

DEFINITION. Bitonic (P) stands for: each segment forms a bitonic sequence.

Let now each segment be subdivided into 2^{P-Q} subsegments, or *boxes*, of 2^Q elements each. If the elements of a segment were sorted in some order, each element would end up in its *destination box* according to that order.

DEFINITION. In_Boxes(P,Q) stands for: within each segment the elements are (already) in their destination boxes according to $\Omega(b_{D-1:P})$-order.

LEMMA 2. *If* $0 \le P \le D$, *then*

(a) In_Boxes(P,P);

(b) *if* In_Boxes(P,0), *then* Ordered(P);

(c) *for* $P \ge 1$, *if* Ordered(P-1), *then* Bitonic(P).

PROOF. As to (a), In_Boxes(P,P) means that the boxes coincide with the segments. As there is only one destination box per segment, each element of a segment must be in its destination box. As to (b), if In_Boxes(P,0), the boxes have one element. So if within a segment the elements are in their destination box, they must be in place and each segment is sorted. (Actually, In_Boxes(P,0) is equivalent to Ordered(P).) As to (c), if Ordered(P-1), then for each segment of length 2^P the lower half and the upper half are both sorted in $\Omega(b_{D-1:P-1})$-order. For the lower half $b_{P-1} = 0$ and for the upper half $b_{P-1} = 1$, so the upper half is sorted in the reverse order of the order of the lower half. The whole segment is then bitonic. □

DEFINITION. ich(H:P,Q), $0 \le Q < P \le H+1 \le D$, stands for the following action:

for all b, interchange a[b with $b_Q = 0$] and
a[b with $b_Q = 1$] if they are not in $\Omega(b_{H:P})$-order.

LEMMA 3. *If* $0 \le Q < P \le D$, *then*

{Bitonic(Q+1) & In_Boxes(P,Q+1)}ich(D-1:P,Q){Bitonic(Q)
& In_Boxes(P,Q)}.

PROOF. This lemma is a generalization of Lemma 1 for sequences whose length is a power of two. (Lemma 1 is obtained from Lemma 3 by taking P = D and Q = D - 1.) The generalization follows by applying Lemma 1 to each (bitonic) box of length 2^{Q+1} in a segment of length 2^P. The boxes are then "refined" by splitting each box into two halves (each of which receives again a bitonic sequence), and its elements are divided over the two new boxes of length

2^Q according to $\Omega(D-1:P)$-order. Since the elements were already in their destination boxes of length 2^{Q+1}, they now reach their destination box of length 2^Q. □

3. FIRST VERSION OF THE ALGORITHM

```
{In_Boxes(0,0)}
{Ordered(0)}
for P = 1,2,...,D do
          {Ordered(P-1)}
          {Bitonic(P) & In_Boxes(P,P)}
          for Q = P-1,P-2,...,0 do
               {Bitonic(Q+1) & In_Boxes(P,Q+1)}
               ich(D-1:P,Q)
               {Bitonic(Q) & In_Boxes(P,Q)}
          end for Q
          {In_Boxes(P,0)}
          {Ordered(P)}
end for P
{Ordered(D)}.
```

Correctness Proof: Each of the verification conditions is either trivially satisfied or is an immediate consequence of Lemmas 2 and 3. The final assertion Ordered(D) asserts that the whole array is sorted in ≤-order. □

4. ALGORITHM FOR BITONIC SORT ON ULTRACOMPUTERS

If the operation ich(D-1:P,Q) could be realized in time $\Theta(1)$, the algorithm would take time $\Theta(D^2)$. If the elements of the array a are stored in consecutive processors of an ultracomputer, it is, however, not possible to compare two arbitrary elements immediately, since not all processors are directly connected. Consecutive processors *are* connected, so operations of the form ich(H:P,0) operate in time $\Theta(1)$. Other connections are the *shuffle* lines, connecting each processor $b_{D-1:0}$ to the processor $\sigma(b_{D-1:0}) = b_0 b_{D-1:1}$.

Through this connection, the following *parallel* assignments take time $\Theta(1)$:

shuffle: for all b, $a[b] := a[\sigma(b)]$;
unshuffle: for all b, $a[\sigma(b)] := a[b]$.

The two operations permute a and are each other's inverse.

Let shuffle^Q stand for the null action if $Q = 0$, and for shuffle^{Q-1}; shuffle if $Q \geq 1$. So shuffle^Q stands for:

for all b, $a[b] := a[\sigma^Q(b)]$.

Let unshuffle^Q be defined similarly.

<u>LEMMA 4</u>. ich(D-1:P,Q), *where* $0 \leq Q < P \leq D$, *is equivalent to*

unshuffle^Q; ich(D-Q-1:P-Q,0); shuffle^Q.

<u>PROOF</u>. The operation ich(D-1:P,Q) stands for

for all b, interchange a[b with $b_Q = 0$] and
a[b with $b_Q = 1$] if they are not in $\Omega(b_{D-1:P})$-order.

Using the assignment rule, this is seen to be equivalent to

for all b, $a[\sigma^Q(b)] := a[b]$ (or unshuffle^Q);
for all b, interchange $a[\sigma^Q(b)$ with $b_Q = 0]$
and $a[\sigma^Q(b)$ with $b_Q = 1]$
if they are not in $\Omega(b_{D-1:P})$-order;
for all b, $a[b] := a[\sigma^Q(b)]$ (or shuffle^Q).

Substituting in the middle part $\sigma^{-Q}(b')$ for b, using $b_R = \sigma^{-Q}(b')_R = b'_{R-Q}$ for $R \geq Q$, we obtain

for all b', interchange a[b' with $b'_0 = 0$]
and a[b' with $b'_0 = 1$]
if they are not in $\Omega(b_{D-Q-1:P-Q})$-order.

This is exactly the meaning of ich(D-Q-1:P-Q,0). □

Using Lemma 4, the algorithm may be transformed to:

<u>for</u> P = 1,2,...,D <u>do</u>
    <u>for</u> Q = P-1,P-2,...,0 <u>do</u>
        unshuffle^Q;
        ich(D-Q-1:P-Q,0);
        shuffle^Q
    <u>end</u> <u>for</u> Q
<u>end</u> <u>for</u> P.

This intermediate version would require time $\Theta(D^3)$.

<u>LEMMA 5</u>. *For* K ≥ 0

$\text{LOOP}_K \equiv$ <u>for</u> Q = K,K-1,...,0 <u>do</u> unshuffle^Q; S(Q); shuffle^Q <u>end</u>,

where S(Q) *is any statement depending on* Q, *is equivalent to*

unshuffle^{K+1}; LOOP'_K, *where*

$\text{LOOP}'_K \equiv$ <u>for</u> Q = K,K-1,...,0 <u>do</u> shuffle; S(Q) <u>end</u>.

<u>PROOF</u>. By induction on K. LOOP_0 and unshuffle; LOOP'_0 reduce to an obvious equivalence. For larger K, we see that LOOP_K is equivalent to

unshuffle^K; S(K); shuffle^K; LOOP_{K-1}

by moving the first execution of the loop body outside. By the inductive hypothesis, this is equivalent to

unshuffle^K; S(K); shuffle^K; unshuffle^K; LOOP'_{K-1},

which again is equivalent to

unshuffle^{K+1}; shuffle; S(K); LOOP'_{K-1}.

Moving shuffle; S(K) inside the loop, we obtain

unshuffle^{K+1}; LOOP'_K. □

By this lemma, we finally obtain

Algorithm for bitonic sort on ultracomputers:

```
for P = 1,2,...,D do
  unshuffle^P;
  for Q = P-1,P-2,...,0 do
    shuffle;
    ich(D-Q-1:P-Q,0)
  end for Q
end for P.
```

This algorithm clearly takes time $\Theta(D^2) = \Theta((\log N)^2)$.

REMARK. The idea of using shuffles to implement bitonic sort is described in STONE [4].

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