CS 467/567: Divide and Conquer on the PRAM

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Binary search

- Problem: Given a sequence $S_{1..n}$ sorted in increasing order and a value x, find the subscript k such that $S_i = x$
- If n processors are available the problem can be solved in constant time:
  1. All processors read x
  2. Each processor P_i compares x with S_i
  3. All processors P_i (if any) that found $x = S_i$ write j into k using $\min$ as combining operator
  - Good running time but far from optimal
  - Other CW models (Priority, Arbitrary, etc.) can also be used to break ties
- Naïve divide and conquer approach for $N < n$ processors:
  1. Divide the sequence S into N roughly equally sized subsequences (of length $O(n/N)$ each)
  2. Each processor performs a sequential binary search to search for x in one subsequence
  3. Those procesors (if any) that found x write the respective index into k using $\min$ as combining operator
  - $O(\log(n/N))$ running time → faster than the sequential algorithm but not considerably so

Parallel binary search

- N processors used to perform an $N + 1$-way (rather than binary) search
- Sequence of stages; in the first stage all the sequence is under consideration, in subsequent stages only a subsequence will be under consideration
- At each stage the sequence under consideration is split into $N + 1$ subsequences
  1. Each processor P_i compares x with the elements s at the right boundary of the i-th subsequence
  2. If $x < s$ then all the elements in the $i + 1$-st and higher subsequences can be discarded
  3. If $x > s$ then all the elements in the i-th and lower subsequences can be discarded
  4. If $x = s$ then the index has been found
- This process reduces the sequence under considertion N times rather than just halving it (like in the sequential case)
- The overall running time is thus $O(\log_N n)$

Merging

- Problem: Given two sequences of numbers (or more generally comparable values) $A = \langle a_1, a_2, \ldots, a_r\rangle$ and $B = \langle b_1, b_2, \ldots, b_s\rangle$ sorted in nondecreasing order, compute the sequence $C = \langle c_1, c_2, \ldots, c_{r+s}\rangle$ such that each c_i belongs to either A or B, ech a_i and b_i appear exactly once in C, and the sequence C is sorted in nondecreasing order

  Algorithm RAM-MERGE(A, B) **returns** C:
  1. $i \leftarrow 1$, $j \leftarrow 1$
  2. **for** $k = 1$ **to** $r + s$ **do**
     1. **if** $a_i < b_j$ **then** $c_k \leftarrow a_i$, $i \leftarrow i + 1$
     2. **else** $c_k \leftarrow b_j$, $j \leftarrow j + 1$
  - $O(n)$ running time (optimal)
- Requirements for the parallel algorithm:
  - Sublinear and adaptive number of processors
  - Running time substantially smaller than the sequential running time, and also adaptive
  - Optimal

PRAM MERGE

Assume (without loss of generality) that $r \leqslant s$

Algorithm PRAM-MERGE(A, B) **returns** C:

- Select $N-1$ elements from A that divide A into N sequences of approximately equal size; call this sequence $A' = \langle a'_1, a'_2, \ldots \rangle$. Similarly find the sequence $B' = \langle b'_1, b'_2, \ldots \rangle$ that divide B into N sequences of roughly the same size (constant time):
  1. **for** $i = 1$ **do in parallel** $a'_i \leftarrow a_{i\lceil r/N \rceil}$, $b'_i \leftarrow b_{i\lceil s/N \rceil}$
- Merge A' and B' into a sequence of triples $V = \langle v_1, v_2, \ldots v_{2N-2} \rangle$, where each triple consists of an element of A' or B', its position in A' or B', and the name of the sequence of origin (A or B) ($O(\log N)$ time):
  1. **for** $i = 1$ **to** N **do in parallel**
     1. Processor P_i uses binary search on B' to find the smallest j such that $a'_i < b'_j$
     2. **if** j exists **then** $v_{i+j-1} \leftarrow (a'_i, i.A)$ **else** $v_{i+N-1} \leftarrow (a'_i, i, A)$
  2. **for** $i = 1$ **to** N **do in parallel**
     1. Processor P_i uses binary search on A' to find the smallest j such that $b'_i < a'_j$
     2. **if** j exists **then** $v_{i+j-1} \leftarrow (b'_i, i.B)$ **else** $v_{i+N-1} \leftarrow (b'_i, i, A)$

PRAM MERGE (CONT'D)

- Each processor merges and inserts into C the elements of two subsequences, one from A and one from B. The indices of the two elements (one in A and one in B) at which each processor begins merging are first computed and stored in an array Q of pairs ($O(r + s/N)$ time):
  1. $Q_1 \leftarrow (1, 1)$
  2. **for** $i = 2$ **to** N **do in parallel**
     1. **if** $v_{2i-2} = (a'_k, k, A)$ **then** processor P_i uses binary search on B to find the smallest j such that $b_j > a'_k$ $Q_i \leftarrow (k\lceil r/N \rceil, j)$
     2. **else** processor P_i uses binary search on A to find the smallest j such that $a_j > b'_k$ $Q_i \leftarrow (j, k\lceil s/N \rceil)$
  3. **for** $i = 1$ **to** N **do in parallel**
     1. Processor P_i uses RAM-MERGE and $Q_i = (x, y)$ to merge two subsequences beginning at a_x and b_y and places the result in C beginning at index $x + y - 1$. The merge continues until either (a) an element larger than or equal to the firt component of v_{2i} in each of A and B (when $i \leqslant N - 1$), or (b) no elements are left in either A or B (when $i = N$)

Running time: $O(n/N + \log n)$ → optimal algorithm for $N \leqslant n/\log n$

LIGHTNING FAST PRAM SORTING

Algorithm CRCW-SORT$(S_{1..n})$ **returns** $S'_{1..n}$:

1. **for** $i = 1$ **to** n **do in parallel**
   for $j = 1$ **to** n **do in parallel**
   1. **if** $s_i > s_j \lor s_i = s_j \land i > j$
   2. **then** P_{ij} writes 1 in c_i using $+$ as combining operation
   3. **else** P_{ij} writes 0 in c_i using $+$ as combining operation
2. **for** $i = 1$ **to** n **do in parallel**
   1. P_{i1} stores S_i into S'_{1+c_i}

- Method called enumeration or rank sorting
- Contant running time
- $O(n^2)$ processors → $O(n^2)$ cost (not optimal)
- Likely of not a great practical value (number of processors very high)

ENUMERATION SORTING ON THE CREW PRAM

- What about the CREW PRAM?
- Can still compare one pair of values (s_i, s_j) in each processor, but we cannot write all the results c_i in a single memory location
- Solution:
  1. If $s_i > s_j \lor s_i = s_j \land i > j$ then processor P_{ij} writes 1 into c_{ij}; otherwise P_{ij} writes 0 into c_{ij}
  2. Set c_i to $\sum_{j=1}^{n} c_{ij}$ then continue as in the CRCW algorithm
- Extra step: $c_i \leftarrow \sum_{j=1}^{n} c_{ij}$
  - Keep adding (in parallel) pairs of values until a single value remains
  - $O(\log n)$ time using n processors
- Overall running time: $O(\log n)$ using $O(n^2)$ processors

Optimal sorting on the CREW PRAM

Algorithm CREW-SORT($S_{1..n}$) **returns** $S_{1..n}$:

1. Distribute equal size subsequences of S to the N processors. Each processor will then sort its subsequence sequentially ($O((n/N)\log(n/N))$ time)
2. Keep merging pairwise adjacent subsequences (in parallel) until one sequence (of length n) is obtained (using PRAM-MERGE)
   - N/k subsequences (of length kn/N each) to merge in iteration k
   - Allocate $O(k)$ processor per pair of subsequences for each merge → $O(n/N + \log(kn/N)) = O(n/N + \log n)$ time per iteration
   - $O(\log N)$ iterations → $O((n/N)\log N + \log n \log N)$ overall time

- Running time: $O((n/N)\log n + \log^2 n)$
- Cost: $O(n\log n + N\log^2 n)$ → optimal for $N \leqslant n/\log n$

- We can also sort faster ($O(\log n)$ time with $O(n)$ processors, still optimal), but such an algorithm does not scale well

Convex Hull on the PRAM

Algorithm PRAM-CONVEX-HULL(n, Q):

1. Sort the points in Q according to their x coordinate
2. Partition Q into $n^{1/2}$ sets $Q_1, Q_2, \ldots, Q_{n^{1/2}}$ of $n^{1/2}$ points each such that the sets are separated by vertical lines and Q_i is to the left of Q_j iff $i < j$
3. **for** $i = 1$ to $n^{1/2}$ **do in parallel**
   1. **if** $|Q_i| < 3$ **then** $CH(Q_i) \leftarrow Q_i$
   2. **else** $CH(Q_i) \leftarrow$ PRAM-CONVEX-HULL($n^{1/2}, Q_i$)
4. **return** PRAM-MERGE-CH($CH(Q_1), CH(Q_2), \ldots, CH(Q_{n^{1/2}})$)

- Let the algorithm use $O(n)$ processors
- Step 1 doable in $O(\log n)$ time
- Step 2 takes constant time (the sets Q_i are all subsequences of Q)
- Step 4 takes $O(\log n)$ time
- Overall the running time is $t(n) = t(n^{1/2}) + c\log n$ and so $t(n) = O(\log n)$
- Therefore cost is $O(n\log n)$ → optimal (non-output sensitive complexity)

Convex Hull on the PRAM (cont'd)

Algorithm PRAM-MERGE-CH($CH(Q_1), CH(Q_2), \ldots, CH(Q_{n^{1/2}})$):

- Let u be the leftmost point of $CH(Q_1)$ and v the rightmost point of $CH(Q_{n^{1/2}})$
- Identify the upper hull:
  1. Assign $O(n^{1/2})$ processors to each $CH(Q_i)$
  2. Each processor assigned to $CH(Q_i)$ finds the upper tangent common between $CH(Q_i)$ and $CH(Q_j)$ for some $i \neq j$
  3. Between all common tangents between $CH(Q_i)$ and $CH(Q_j)$, $j < i$ let L_i (tangent with $CH(Q_i)$ at point l_i) be the tangent with the smallest slope
  4. Between all common tangents between $CH(Q_i)$ and $CH(Q_j)$, $j > i$ let R_i (tangent with $CH(Q_i)$ at point r_i) be the tangent with the smallest slope
  5. If the angle formed by L_i and R_i is smaller than 180 degrees then no points from $CH(Q_i)$ are in the upper hull; otherwise include in the upper hull all the points between l_i and r_i (inclusive)
  6. Identify the upper hull as all the points from u to r_1, then all the points identified above, then all the points from $r_{n^{1/2}}$ to v (inclusive)
- Identify the lower hull (similar to the upper hull)
  - The lower hullis identified as above but this time u and v are excluded
- Return the union of the upper and lower hulls (array packing)

Convex Hull on the PRAM (cont'd)

Computing the upper tangent of $CH(Q_i)$ and $CH(Q_j)$ in $O(\log n)$ time:

- Let s and w be the middle points in the (sorted) upper hulls from $CH(Q_i)$ and $CH(Q_j)$
- If $\overline{sw}$ is the upper tangent of $CH(Q_i)$ and $CH(Q_j)$ then we are done (Case a)
- Otherwise repeat from Step 1 but excluding at least half the points of at least one upper hull (Cases b–h)