Chapter 2
Sorting with a PRAM

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### Very simple Algorithm (Idea)

|   | 22 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 12 |
|   | 33 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 7 | 14 |
|   | 41 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 9 | 22 |
|   | 26 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 5 | 23 |
|   | 59 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 14 | 26 |
|   | 57 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 13 | 27 |
|   | 52 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 11 | 33 |
|   | 61 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 15 | 34 |
|   | 27 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 6 | 41 |
|   | 49 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 10 | 49 |
|   | 67 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 16 | 52 |
|   | 23 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 56 |
|   | 56 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 12 | 57 |
|   | 14 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 59 |
|   | 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 61 |
|   | 34 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 8 | 67 |

|   | 34 | 12 | 14 | 56 | 23 | 67 | 49 | 27 | 61 | 52 | 57 | 59 | 26 | 41 | 33 | 22 |
Very simple Sorting Algorithm

- Idea: Compute the position for each element.
- Compare pairwise all elements and count the number of smaller elements.
- Use $n^2$ processors.
- Programm: SimpleSort
  - Eingabe: $s_1, \ldots, s_n$.
  - for all $P_{i,j}$ where $1 \leq i, j \leq n$ do in parallel
    - if $s_i > s_j$ then $P_{i,j}(1) \rightarrow R_{i,j}$ else $P_{i,j}(0) \rightarrow R_{i,j}$
  - for all $i$ where $1 \leq i \leq n$ do in parallel
    - for all $P_{i,j}$ where $1 \leq j \leq n$ do in parallel
      - Processors $P_{i,j}$ bestimmen $q_i = \sum_{l=1}^{n} R_{i,l}$.
      - $P_i(s_i) \rightarrow R_{q_i+1}$.

- Complexity: $T(n) = O(\log n)$ and $P(n) = n^2$.
- Efficiency: $\frac{O(n\log n)}{n^2 \cdot O(\log n)} = O\left(\frac{1}{n}\right)$.
- Model: CREW.
Improved Algorithm for CREW

- Work with $P(n)$ processors ($P(n) \leq n$).
- Split the input in blocks of size $O(n/P(n))$. $O(1)$
- Sort parallel each block. $O(n/P(n) \cdot \log(n/P(n)))$
- Merge the blocks pairwise and parallel. $O(n/P(n) + \log n) \cdot O(\log P(n))$

**Complexity:** $T(n) = O(n/P(n) \cdot \log n + \log^2 n)$.

**Efficiency:** $Eff(n) = \frac{O(n \log n)}{O(P(n)) \cdot O(n/P(n) \cdot \log n + \log^2 n)} = \frac{O(n \log n)}{O(n \cdot \log n + P(n) \cdot \log^2 n)}$

- Is $O(1)$ for $P(n) \leq n/\log n$. 
Improved Algorithm EREW

- Exchange the merge algorithm.
- Recall $T_{\text{Merging}(\text{EREW})}(n) = \Theta(n/P(n) + \log n \cdot \log P(n))$.
- $T(n) = O(n/P(n) \cdot \log(n/P(n)) + O(n/P(n) \cdot \log P(n) + \log n \cdot \log^2 P(n))$
- $T(n) = O((n/P(n) + \log^2 n) \cdot \log n)$
- Efficiency:

$$Eff(n) = \frac{O(n \log n)}{O(P(n) \cdot ((n/P(n) + \log^2 n) \cdot \log n))}$$

- Is $O(1)$ if $P(n) < n/\log^2 n$. 
Lower Bound

Theorem:
For any parallel sorting algorithm \( Srt \) with \( P_{Srt}(n) = O(n) \) hold:

\[
T_{Srt}(n) = \Omega(\log(n)).
\]

Proof:
- Lower bound for sequential is \( \Theta(n \log n) \).
- One needs \( O(n \log n) \) comparisons.
- In each parallel step are at most \( o(n) \) comparisons possible.
- Thus with less steps we have a contradiction to the lower bound for sequential.

Situation at this point:
- Inefficient algorithms with: \( T(n) = O(\log n) \) and \( P(n) = n^2 \).
- Nearly efficient algorithm with: \( T(n) = O(\log^2 n) \) and \( P(n) = o(n) \).
Basic Operation for Sorting

- Identify basic operation for sorting.
- Assume: sorting key is $s_1, \ldots, s_n$.
- Programm: `compare_exchange(i,j)`
  ```
  if $s_i > s_j$ then exchange $s_i \leftrightarrow s_j$
  ```
- Symbolic view (Batcher):
  ```
  y  \hspace{2cm} \max(x, y) \\
  x  \hspace{2cm} \min(x, y)
  ```
- Basic building block for sorting networks.
- Base for Odd-Even merge
- Form this we build the optimal algorithm by Cole
Odd-even Merge (Definition)

- **Input:** Sequence $S = (s_1, s_2, \cdots, s_n)$. (O.E.d.A. $n$ even)
- Let $Odd(S)$ [$Even(S)$] be the elements of $S$ with odd [even] index.
- Let $S' = (s'_1, s'_2, \cdots, s'_n)$ be a second sequence.
- Then we define: $interleave(S, S') = (s_1, s'_1, s_2, s'_2, \cdots, s_n, s'_n)$.

- $T_{interleave}(n) = O(1)$ mit $P_{interleave}(n) = O(n)$
Odd-even Merge (Definition)

- **Programm:** `odd_even(S)`
  
  for all $i$ where $1 < i < n$ and $i$ even do in parallel
  
  `compare_exchange(i, i + 1)`.

- $T_{\text{compare\_exchange}}(n) = O(1)$ mit $P_{\text{compare\_exchange}}(n) = O(n)$
Odd-even Merge (Definition)

Programm: \( \text{join1}(S, S') \)

\( \text{odd\_even(interleave}(S, S')) \)

\( T_{\text{join1}}(n) = O(1) \) mit \( P_{\text{join1}}(n) = O(n) \)
Sorting with Merging

- Programm: \(\text{odd\_even\_merge}(S, S')\)
  
  \[
  \text{if } |S| = |S'| = 1 \text{ then merge with } \text{compare\_exchange}.
  \]
  
  \[
  S_{\text{odd}} = \text{odd\_even\_merge}(\text{odd}(S), \text{odd}(S')).
  \]
  
  \[
  S_{\text{even}} = \text{odd\_even\_merge}(\text{even}(S), \text{even}(S')).
  \]
  
  \[
  \text{return } \text{join1}(S_{\text{odd}}, S_{\text{even}}).
  \]

- \(T_{\text{odd\_even\_merge}}(n) = O(\log n)\) mit \(P_{\text{odd\_even\_merge}}(n) = O(n)\)

**Theorem:**

The algorithm \(\text{odd\_even\_merge}\) sorts two already sorted sequences into one.

Proof follows.
Sorting Networks

Theorem:
There exists a sorting algorithm with $T(n) = O(\log^2 n)$ and $P(n) = n$.

Proof: use divide and conquer, and merging of depth $O(\log n)$.

Theorem:
There exists a sorting network of size $O(n \log^2 n)$.

Proof: All calls to `compare_exchange` operation are independent form the input (oblivious algorithm).
The 0-1 Principle

**Theorem:**
If a sorting network $X$, resp. sorting algorithm is correct for all 0-1 inputs, then it is also correct for any input.

**Proof (by contradiction):**

- Let $f(x)$ be non-decreasing function: $f(s_i) \leq f(s_j) \iff s_i \leq s_j$.
- If $X$ sorts the sequence $(a_1, a_2, \cdots, a_n)$ to $(b_1, b_2, \cdots, b_n)$, then if $X$ gets $(f(a_1), f(a_2), \cdots, f(a_n))$ then the output $(f(b_1), f(b_2), \cdots, f(b_n))$ is also sorted.
- Assume $b_i > b_{i+1}$ and $f(b_i) \neq f(b_{i+1})$, then we have $f(b_i) > f(b_{i+1})$ in the “sorted” sequence $(f(b_1), f(b_2), \cdots, f(b_n))$. i.e errors may be kept under the function $f$.
- Choose now $f$: $f(b_j) = 0$ for $b_j < b_i$ and $f(b_j) = 1$ otherwise.
- Thus the sequence $(f(b_1), f(b_2), \cdots, f(b_n))$ is not sorted, because of $f(b_i) = 1$ and $f(b_{i+1}) = 0$.
- This is a contradiction.
Correctness of the Merging

Theorem:
The algorithm `odd_even_merge` sorts two sorted sequences into a single one.

Proof:

- $S$ has the form: $S = 0^p 1^{m-p}$ for some $p$ with $0 \leq p \leq m$.
- $S'$ has the form: $S' = 0^q 1^{m'-q}$ for some $q$ with $0 \leq q \leq m'$.
- Thus the sequence $S_{odd}$ has the form $0^{\lceil p/2 \rceil + \lceil q/2 \rceil} 1^*$
- And $S_{even}$ has the form $0^{\lfloor p/2 \rfloor + \lfloor q/2 \rfloor} 1^*$.
- Define: $d = \lceil p/2 \rceil + \lceil q/2 \rceil - \lfloor p/2 \rfloor - \lfloor q/2 \rfloor$
- Depending on $d$ we consider three cases: $d = 0$, $d = 1$ and $d = 2$. 
Correctness of the Merging

If \( d = 0 \): Then we have: \( p \) and \( q \) are even.
- The *interleave* step of *join1* has the form:

\[
\text{interleave}(S_{\text{odd}}, S_{\text{even}}) = (00)^{(p+q)/2}1^{m+m'-p-q}
\]
- The resulting sequences is already sorted.
- The *compare_exchange* step keeps the order.

If \( d = 1 \): Then we have: \( p \) is odd and \( q \) is even.
- The *interleave* step of *join1* has the form:

\[
\text{interleave}(S_{\text{odd}}, S_{\text{even}}) = (00)^{\lfloor(p+q)/2\rfloor}01^{m+m'-p-q}
\]
- The resulting sequences is already sorted.

If \( d = 2 \): Then we have: \( p \) and \( q \) are odd.
- The *interleave* step of *join1* has the form:

\[
\text{interleave}(S_{\text{odd}}, S_{\text{even}}) = (00)^{\lfloor(p+q)/2\rfloor}101^{m+m'-p-q}
\]
- The *compare_exchange* step will exchange the 1 on position \( 2r \) with the 0 on position \( 2r + 1 \).
Correlar:
The correctness of a merge network may be tested in time $O(n^2)$.

Proof: Test all inputs of the form $(0^p1^{m-p},0^q1^{m'-q})$.

Theorem:
The test for correctness of a sorting network is NP-hard.

Proof: Literature.
Situation

- Aim: Fast optimal algorithm.
- So far $T(n) = \log^2 n$ bei $P(n) = O(n)$.
- So far: Two loop for merging and sorting.
- Idea: make one loop faster, i.e. the merging in $O(1)$.
- Problem: With no further information we need $\Theta(\log n)$ steps.
- Idea: compute this additional information during the sorting.
- Choose as additional information nice splitting points for merging.
- I.e choose positions which split the blocks to be merged of constants size.
- Problem: How to compute these points?
- Solution is the base for the algorithm of Cole.
The Merging-Tree, a View
Idea

- Before merging two sequences we will merge two sub-sequences.
- Choose as sub-sequence each $k$-th element of the original sequence.
- These sub-sequences will be used as crutch/support to do the final merging.
- I.e. these sub-sequences are used as a kind of “preview”.
- Using these crutch points we will be able to do the merging in $O(1)$ time.
- Total running time will be $O(\log n)$.
- The additional effort should be at most $O(1)$. 
The Merging-Tree, a View

Each Processor starts with 256 elements
Definition

- Let $J$ and $K$ be two sorted sequences.
- Note: without additional information we could not merge $J$ and $K$ in $O(1)$ time with $O(n)$ processors.
- Let $L$ be a third sequence, which will be called in the following **good sampler** for $J$ and $K$.
- Informal: $|L| < |J|$ and the elements of $L$ are evenly spread in $J$.
- Let $a < b$, $c$ is between $a$ and $b$ iff $a < c \leq b$.
- The rank of $e$ in $S$ is $\text{rng}(e, S) = |\{x \in S \mid x < e\}|$.
- Notation: $\text{Rng}_{A,B}$ is the function $\text{Rng}_{A,B} : A \mapsto \mathbb{N}^{|A|}$ with $\text{Rng}_{A,B}(e) = \text{rng}(e, B)$ for all $e \in A$.
- $\text{Rng}_{A,B}$ is called the rank between $A$ and $B$.
- Depending on the context $\text{Rng}_{A,B}$ could also be an array with $|A|$ elements.
Good Sampler

\[ \text{rng}(e, S) = |\{x \in S \mid x < e\}| \text{ and } Rng_{A,B} : A \mapsto \mathbb{N}^{\|A\|} \text{ with } Rng_{A,B}(e) = \text{rng}(e, B) \]

**Definition:**

We call \( L \) a good sampler of \( J \), iff:

- \( L \) and \( J \) are sorted.
- Between any \( k + 1 \) succeeding elements of \( \{-\infty\} \cup L \cup \{+\infty\} \) are at most \( 2 \cdot k + 1 \) many elements in \( J \).

**Example:**

- Let \( S \) be a sorted sequence
- Let \( S_1 \) be the sequence consisting of each fourth element of \( S \).
- Then \( S_1 \) is a good sampler of \( S \).
- Let \( S_2 \) be the sequence consisting of each second element of \( S \).
- Then \( S_1 \) is a good sampler of \( S_2 \).
- Example (\( k = 1 \)): \( 1, 2, 3, 4 \).
- Example (\( k = 3 \)): \( 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 \).
Merging using a Good Sampler

rng(e, S) = |{x ∈ S | x < e}| and Rng_{A,B} : A → IN^{|A|} with Rng_{A,B}(e) = rng(e, B)

Let J, K and L be sorted sequences.
Let L be a good sampler of both J and K.
Let L = (l_1, l_2, ⋯, l_s).
Programm: merge_with_help(J, K, L)
for all i where 1 ≤ i ≤ s do in parallel
    Assign J_i = \{x ∈ J | l_{i-1} < x ≤ l_i\}.
    Assign K_i = \{x ∈ K | l_{i-1} < x ≤ l_i\}.
    Assign res_i = merge(J_i, K_i).
return (res_1, res_2, ⋯, res_s).

Situation:

<p>| | | | | | | | | |</p>
<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>L_3</td>
<td>L_4</td>
<td>L_5</td>
<td>L_6</td>
<td>L_7</td>
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<td>L_9</td>
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<tr>
<td>l_1</td>
<td>l_2</td>
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<td>l_4</td>
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<td>l_6</td>
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<tr>
<td>K_1</td>
<td>K_2</td>
<td>K_3</td>
<td>K_4</td>
<td>K_5</td>
<td>K_6</td>
<td>K_7</td>
<td>K_8</td>
<td>K_9</td>
</tr>
</tbody>
</table>
Merging using a Good Sampler (Example)

\[ \text{rng}(e, S) = |\{x \in S \mid x < e\}| \quad \text{and} \quad \text{Rng}_{A,B} : A \mapsto \mathbb{N}^{|A|} \quad \text{with} \quad \text{Rng}_{A,B}(e) = \text{rng}(e, B) \]

- \( K = (1, 4, 6, 9, 11, 12, 13, 16, 19, 20) \)
- \( J = (2, 3, 7, 8, 10, 14, 15, 17, 18, 21) \)
- \( L = (5, 10, 12, 17) \)

Then we have:

<table>
<thead>
<tr>
<th>( i )</th>
<th>( K_i )</th>
<th>( J_i )</th>
<th>( \text{merge}(K_i, J_i) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(1, 4)</td>
<td>(2, 3)</td>
<td>(1, 2, 3, 4)</td>
</tr>
<tr>
<td>2</td>
<td>(6, 9)</td>
<td>(7, 8, 10)</td>
<td>(6, 7, 8, 9, 10)</td>
</tr>
<tr>
<td>3</td>
<td>(11, 12)</td>
<td>\emptyset</td>
<td>(11, 12)</td>
</tr>
<tr>
<td>4</td>
<td>(13, 16)</td>
<td>(14, 15, 17)</td>
<td>(13, 14, 15, 16, 17)</td>
</tr>
<tr>
<td>5</td>
<td>(19, 20)</td>
<td>(18, 21)</td>
<td>(18, 19, 20, 21)</td>
</tr>
</tbody>
</table>

Result: \( (1, 2, 3, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21) \)
Merging with good sampler (running time)

\[ \text{rng}(e, S) = |\{ x \in S \mid x < e \}| \quad \text{and} \quad \text{Rng}_{A,B} : A \mapsto \mathbb{N}^{\left| A \right|} \quad \text{with} \quad \text{Rng}_{A,B}(e) = \text{rng}(e, B) \]

Lemma:

If \( L \) is a good sampler for \( K \) and \( J \).

If \( \text{Rng}_{L,J}, \text{Rng}_{L,K}, \text{Rng}_{K,L} \) and \( \text{Rng}_{J,L} \) is known, then we have:

\[ T_{\text{merge \_ with \_ help}(J,K,L)} = O(1) \quad \text{with} \quad P_{\text{merge \_ with \_ help}(J,K,L)} = O(|J| + |K|). \]

Proof:

- The same way as in the merging introduced in the last chapter.
- Each processor uses \( \text{Rng}_{L,J} \) resp. \( \text{Rng}_{L,K} \) to know the area to read its input sequences.
- Each processor uses \( \text{Rng}_{J,L} \) and \( \text{Rng}_{K,L} \) to know the area to write its output sequence.
Properties of Good Samplers

\[ \text{rng}(e, S) = |\{x \in S \mid x < e\}| \quad \text{and} \quad \text{Rng}_{A,B} : A \mapsto \mathbb{N}^{|A|} \quad \text{with} \quad \text{Rng}_{A,B}(e) = \text{rng}(e, B) \]

Lemma:

If \( X \) is a good sampler for \( X' \) and \( Y \) is a good sampler for \( Y' \), then \( \text{merge}(X, Y) \) is a good sampler for \( X' \) [resp. \( Y' \)].

Proof:

- Consider \( X \) as a good sampler for \( X' \).
- Any additional element make the good sampler just "better".

Note:

\( \text{merge}(X, Y) \) is not necessary a sampler for \( \text{merge}(X', Y') \).
- \( X = (2, 7) \) and \( X' = (2, 5, 6, 7) \).
- \( Y = (1, 8) \) and \( Y' = (1, 3, 4, 8) \).
- \( \text{merge}(X, Y) = (1, 2, 7, 8) \) and \( \text{merge}(X', Y') = (1, 2, 3, 4, 5, 6, 7, 8) \).
- There are 5 elements between 2 and 7.
Properties of Good Samplers

\[ \text{rng}(e, S) = |\{x \in S \mid x < e\}| \text{ and } Rng_{A,B} : A \mapsto \mathbb{N}^{|A|} \text{ with } Rng_{A,B}(e) = \text{rng}(e, B) \]

Lemma:

Let \( X \) be a good sampler for \( X' \) and let \( Y \) be a good sampler for \( Y' \). Then there are at most \( 2 \cdot r + 2 \) elements of \( \text{merge}(X', Y') \) between \( r \) successive elements of \( \text{merge}(X, Y) \).

Proof:

- W.l.o.g. contain \( X \) and \( Y \) elements \(-\infty\) and \(+\infty\).
- Let \( (e_1, e_2, \cdots, e_r) \) successive elements of \( \text{merge}(X, Y) \).
- W.l.o.g. let \( e_1 \in X \).
- Consider now two cases: \( e_r \in X \) and \( e_r \in Y \).
- Let in the following be

\[
\begin{align*}
x &= |X \cap \{e_1, e_2, \cdots, e_r\}| \quad \text{and} \\
y &= |Y \cap \{e_1, e_2, \cdots, e_r\}|.
\end{align*}
\]
Properties of Good Samplers

\((e_1, e_2, \cdots, e_r)\) successive elements of \(merge(X, Y)\) and \(x = |X \cap \{e_1, e_2, \cdots, e_r\}|\) and \(y = |Y \cap \{e_1, e_2, \cdots, e_r\}|\) and

Lemma:

Let \(X\) be a good sampler for \(X'\) and let \(Y\) be a good sampler for \(Y'\). Then there are at most \(2 \cdot r + 2\) elements of \(merge(X', Y')\) between \(r\) successive elements of \(merge(X, Y)\).

Proof: W.l.o.g. let \(e_1 \in X\).

If: \(e_r \in X\)
- Between \(e_1\) and \(e_r\) are at most \(2(x - 1) + 1\) elements of \(X'\).
- Between \(e_1\) and \(e_r\) are at most \(2(y + 1) + 1\) elements of \(Y'\), because they are between \(y + 2\) elements of \(Y\).
- Thus we get: \(2(x - 1) + 1 + 2(y + 1) + 1 = 2 \cdot r + 2\).

Example \(x = 3\) and \(y = 2\):

\[a \in Y \quad e_1 \in X \quad e_2 \in Y \quad e_3 \in X \quad e_4 \in Y \quad e_5 \in X \quad b \in Y\]
Properties of Good Samplers

\((e_1, e_2, \ldots, e_r)\) successive elements of \(\text{merge}(X, Y)\) and \(x = |X \cap \{e_1, e_2, \ldots, e_r\}|\) and \(y = |Y \cap \{e_1, e_2, \ldots, e_r\}|\) and

Lemma:

Let \(X\) be a good sampler for \(X'\) and let \(Y\) be a good sampler for \(Y'\). Then there are at most \(2 \cdot r + 2\) elements of \(\text{merge}(X', Y')\) between \(r\) successive elements of \(\text{merge}(X, Y)\).

Proof: W.l.o.g. let \(e_1 \in X\). If: \(e_r \in Y\)

- Add \(e_0 \in Y\) with \(e_0 < e_1\) to the good sampler.
- Add \(e_{r+1} \in X\) with \(e_r < e_{r+1}\) to the good sampler.
- The elements from \(X'\) between \((e_1, e_2, \ldots, e_r)\) are between \(x + 1\) elements from \(X\).
- The elements from \(Y'\) between \((e_1, e_2, \ldots, e_r)\) are between \(y + 1\) elements from \(Y\).
- Thus we get: \(2x + 1 + 2y + 1 = 2r + 2\).

Example \(x = 2\) and \(y = 2\):

\[ e_0 \in Y \quad e_1 \in X \quad e_2 \in Y \quad e_3 \in X \quad e_4 \in Y \quad e_5 \in X \]
Properties of good sampler

At most $2 \cdot r + 2$ elements of $\text{merge}(X', Y')$ between $r$ successive elements of $\text{merge}(X, Y)$

Definition

Let $\text{reduce}(X)$ be the operation, which chooses from $X$ every forth element.

Lemma:

If $X$ is a good sampler for $X'$ and
$Y$ is a good sampler for $Y'$,
then $\text{reduce}(\text{merge}(X, Y))$ is a good sampler for $\text{reduce}(\text{merge}(X', Y'))$.

Proof:

- Consider $k + 1$ successive elements $(e_1, e_2, \cdots, e_{k+1})$ of $\text{reduce}(\text{merge}(X, Y))$.
- At most $4k + 1$ elements of $\text{merge}(X, Y)$ are between $e_1, e_2, \cdots, e_{k+1}$ including $e_1, e_{k+1}$.
- At most $8k + 4$ elements of $\text{merge}(X', Y')$ are between these $4k + 1$ elements.
- At most $2k + 1$ elements of $\text{reduce}(\text{merge}(X', Y'))$ are between $(e_1, e_2, \cdots, e_{k+1})$. 
Overview to the Algorithm of Cole

- We start with an explanation using a complete binary tree.
- The leave contain the elements to be sorted.
- Interior nodes $v$ “cares” about as many elements as the number of leaves below $v$.
- A node $v$ receives from its sons sequences of already sorted sequences.
- The “length” of the sequences doubles each time.
- Node $v$ receives sequences $X_1, X_2, \cdots, X_r$ and $Y_1, Y_2, \cdots, Y_r$.
- Node $v$ sends to his father sequences $Z_1, Z_2, \cdots, Z_r, Z_{r+1}$.
- Node $v$ updates a interior help-sequence $val_v$.
- It holds: $|X_1| = |Y_1| = |Z_1| = 1$.
- It holds: $|X_i| = 2 \cdot |X_{i-1}|$, $|Y_i| = 2 \cdot |Y_{i-1}|$ and $|Z_i| = 2 \cdot |Z_{i-1}|$. 
One basic Operation of an interior Node \( v \)

- Receives from its sons the two sequences \( X \) and \( Y \).
- Computes: \( val_v = \text{merge\_with\_help}(X, Y, val_v) \).
- Sends to its father: \( \text{reduce}(val_v) \) till \( v \) has sorted all received sequences.
- Sends to its father each second element from \( val_v \), if \( v \) is done with sorting.
- Sends to its father \( val_v \), if \( v \) finishes sorting two steps before.

**Example:**

<table>
<thead>
<tr>
<th>Step</th>
<th>Left</th>
<th>Right</th>
<th>( val_v )</th>
<th>Father</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>8</td>
<td>7,8</td>
<td>∅</td>
</tr>
<tr>
<td>2</td>
<td>3,7</td>
<td>5,8</td>
<td>3,5,7,8</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>1,3,4,7</td>
<td>2,5,6,8</td>
<td>1,2,3,4,5,6,7,8</td>
<td>4,8</td>
</tr>
<tr>
<td>4</td>
<td>1,3,4,7</td>
<td>2,5,6,8</td>
<td>1,2,3,4,5,6,7,8</td>
<td>2,4,6,8</td>
</tr>
<tr>
<td>5</td>
<td>1,3,4,7</td>
<td>2,5,6,8</td>
<td>1,2,3,4,5,6,7,8</td>
<td>1,2,3,4,5,6,7,8</td>
</tr>
</tbody>
</table>
Basic operation of a interior Node $v$

- Receives from its sons the two sequences $X$ and $Y$.
- Computes: $val_v = \text{merge\_with\_help}(X, Y, val_v)$.
- Sends to its father: $\text{reduce}(val_v)$ till $v$ has sorted all received sequences.
- Sends to its father each second element from $val_v$, if $v$ is done with sorting.
- Sends to its father $val_v$, if $v$ finishes sorting two steps before.
- Thus we get the following pattern:

$$
X_1 \quad X_2 \quad X_3 \quad X_4 \quad \cdots \quad X_r \\
Z_1 \quad Z_2 \quad \cdots \quad Z_r \quad Z_{r+1} \quad Z_{r+2}
$$

- If a node $x$ is finished after $t$ steps, then will the father of $x$ be finished after $t + 3$ steps.
- Thus we get a running time of $3 \log n$. 
Invariant:

- Each $X_i$ is a good sampler of $X_{i+1}$.
- Each $Y_i$ is a good sampler of $Y_{i+1}$.
- Each $Z_i$ is a good sampler of $Z_{i+1}$.
- Each $X_i$ is half as big as $X_{i+1}$.
- Each $Y_i$ is half as big as $Y_{i+1}$.
- Each $Z_i$ is half as big as $Z_{i+1}$.
- $|X_1| = |Y_1| = |Z_1| = 1$. 
Situation

- Running time is $O(\log n)$.
- The inner nodes $v$ need $|val_v|$ many processors.
- We still have to proof that the number of processors is in $O(n)$.
- PRAM Model has to be verified.
- Important: The computation of the values $Rng_{X,Y}$ has to be shown.
- These values will be in the following also transmitted and updated.
Computing the Ranks

- In each step will compute: \( \text{merge\_with\_help}(X_{i+1}, Y_{i+1}, \text{merge}(X_i, Y_i)) \).
- Using the Lemma from above we have: \( \text{merge}(X_i, Y_i) \) is a good sampler of \( X_{i+1} \) and \( Y_{i+1} \).
- Let \( L = \text{merge}(X_i, Y_i) \), \( J = X_{i+1} \) and \( K = Y_{i+1} \).
- We have to compute: \( \text{Rng}_{L,J} \), \( \text{Rng}_{L,K} \), \( \text{Rng}_{J,L} \) and \( \text{Rng}_{K,L} \).

**Invariant:**

- Let \( S_1, S_2, \ldots, S_p \) be a sequence of sequences at node \( v \).
- Then node \( c \) also knows: \( \text{Rng}_{S_{i+1}, S_i} \) for \( 1 \leq i < p \).
- Furthermore for each sequence \( S \) is known: \( \text{Rng}_{S,S} \).
Lemma:

Let $S = (b_1, b_2, \ldots, b_k)$ be a sorted sequence, then we may compute the rank of $a \in S$ in time $O(1)$ using $k$ processors.

Proof:

- **Programm**: rng1(a,S)
  
  for all $P_i$ where $1 \leq i \leq k$ do in parallel
  
  if $b_i < a \leq b_{i+1}$ then return $i$

- Note, the program has no write-conflicts.
- Note, it could be changed, to avoid read-conflicts.
Computing the Ranks

**Lemma:**

Let $S_1, S_2, S$ be two sorted sequences with $S = \text{merge}(S_1, S_2)$ and $S_1 \cap S_2 = \emptyset$. Then we may compute $\text{Rnk}_{S_1,S_2}$ and $\text{Rnk}_{S_2,S_1}$ in time $O(1)$ using $O(|S|)$ processors.

**Proof:**

- We do know $\text{Rnk}_{S,S}$, $\text{Rnk}_{S_1,S_1}$, and $\text{Rnk}_{S_2,S_2}$.
- Furthermore we have: $\text{rnk}(a, S_2) = \text{rnk}(a, \text{merge}(S_1, S_2)) - \text{rnk}(a, S_1)$.
- The claim follows directly.
Computing the Ranks

Lemma:

- Let $X$ be a good sampler of $X'$.
- Let $Y$ be a good sampler of $Y'$.
- Let $U = \text{merge}(X, Y)$.
- Assume $\text{Rnk}_{X',X}$ and $\text{Rnk}_{Y',Y}$ are known.

Then we may compute in time $O(1)$ using $O(|X| + |Y|)$ processors $\text{Rnk}_{X',U}$, $\text{Rnk}_{Y',U}$, $\text{Rnk}_{U,X'}$ and $\text{Rnk}_{U,Y'}$.

Proof:

- First we compute $\text{Rnk}_{X',U}$ and $\text{Rnk}_{Y',U}$.
- Then we compute $\text{Rnk}_{X,X'}$ and $\text{Rnk}_{Y,Y'}$.
- Finally we compute $\text{Rnk}_{U,X'}$ and $\text{Rnk}_{U,Y'}$. 

Then we have $\text{rk}(a, S)$ and $\text{Rnk}_{s_1,s_2}$ and $\text{Rnk}_{s_2,s_1}$.
Computing the Ranks \((\text{Rnk}_{X',U})\)

- Let \(X = (a_1, a_2, \ldots, a_k)\).
- Let w.l.o.g. \(a_0 = -\infty\) and \(a_{k+1} = +\infty\).
- Using a good sampler \(X\) we split \(X'\) into \(X'_1, X'_2, \ldots, X'_k, X'_{k+1}\).
- Note: \(\text{Rnk}_{X',X}\) is known.
- Splitting may be done in time \(O(1)\) using \(O(|X|)\) processors.
- Let \(U_i\) be the sequence of elements of \(Y\) which are between \(a_{i-1}\) and \(a_i\).
- Thus we get:

  Programm: \(\text{Rnk}_{X',U}\)
  
  for all \(i\) where \(1 \leq i \leq k + 1\) do in parallel
  
  for all \(x \in X'_i\) do
  
  \(\text{rnk}(x, U) = \text{rnk}(a_{i-1}, U) + \text{rnk}(x, U_i)\)

- Running time \(O(1)\) using \(\sum_{i=1}^{k+1} |U_i|\) processors.
Computing the Ranks \((\text{Rnk}_{X,X'})\)

- Let \(a_i \in X\).
- Let \(a'\) minimal element in \(X'_{i+1}\).
- The rank of \(a_i\) in \(X'\) is the same as the rank of \(a'\) in \(X'\).
- This rank is already known.
- This may be computed in time \(O(1)\) using one processor.
Computing the Ranks \((\text{Rnk}_{U,X'})\)

- Note: \(\text{Rnk}_{U,X'}\) consists of \(\text{Rnk} X, X'\) and \(\text{Rnk} Y, X'\).
- \(\text{Rnk} X, X'\) is already known.
- Still to compute: \(\text{Rnk} Y, X'\).
- \(\text{Rnk} Y, X\) may be computed using the previous lemma.
- We compute \(\text{rnk}(a, X')\) using \(\text{rnk}(a, X)\) and \(\text{Rnk}_{X,X'}\).
- Thus we compute \(\text{Rnk}_{U,X'}\) with \(O(|U|)\) processors and time \(O(1)\).
Computing the Ranks

- Consider the step $merge\_with\_help(J = X_{i+1}, K = Y_{i+1}, L = merge(X_i, Y_i))$.
- Using the invariant we know: $Rnk_{J,X_i}$ and $Rnk_{K,Y_i}$.
- Using the above considerations we may compute: $Rnk_{L,J}$, $Rnk_{L,K}$, $Rnk_{J,L}$ and $Rnk_{K,L}$.
- Still to be computed: $Rnk_{reduce(merge(X_{i+1}, Y_{i+1})), reduce(merge(X_i, Y_i))}$.
- Known: $Rnk_{X_{i+1}, merge(X_i, Y_i)}$ and $Rnk_{Y_{i+1}, merge(X_i, Y_i)}$.
- It is now easy to compute: $Rnk_{X_{i+1}, reduce(merge(X_i, Y_i))}$ and $Rnk_{Y_{i+1}, reduce(merge(X_i, Y_i))}$.
- Also easy to compute: $Rnk_{merge(X_{i+1}, Y_{i+1}), reduce(merge(X_i, Y_i))}$.
Theorem:
We may sort $n$ values on a CREW PRAM using $O(n)$ processors in time $O(\log n)$.

Proof: discussed before.

Theorem:
We may sort $n$ values on a EREW PRAM using $O(n)$ processors in time $O(\log n)$.

Proof: see literature.

Theorem:
There exists a sorting network with $O(n)$ processors and depth $O(\log n)$.

Proof: see literature.
Literature

we have \( \text{rnk}(a, S) \) and \( \text{rnk}_{S_1, S_2} \) and \( \text{rnk}_{S_2, S_1} \)

Literatur:

A. Gibbons, W. Rytter:
Chapter 5.
Questions

- Explain the motivation behind parallel systems.
- Explain the ideas of the different sorting algorithms.
- Explain the different running times of these sorting algorithms.
- Explain the different efficiency of these sorting algorithms.
- Explain the idea of the algorithm of Cole.
- Explain the running time of the algorithm of Cole.
- Explain the number of processors used in the algorithm of Cole.
Legend

- Not of relevance
- implicitly used basics
- idea of proof or algorithm
- structure of proof or algorithm
- Full knowledge