

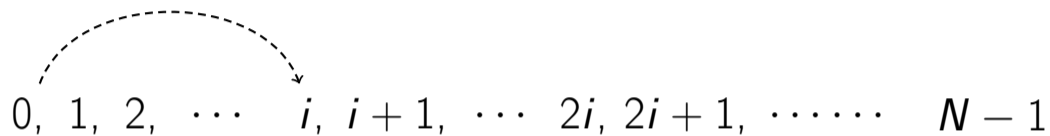
I/O-Efficient Algorithms and Data Structures

Steffan Christ Sølvesten

8th of September, 2023

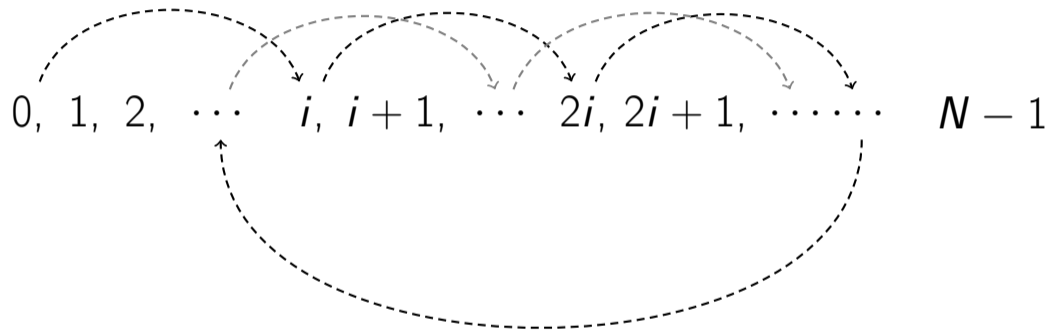


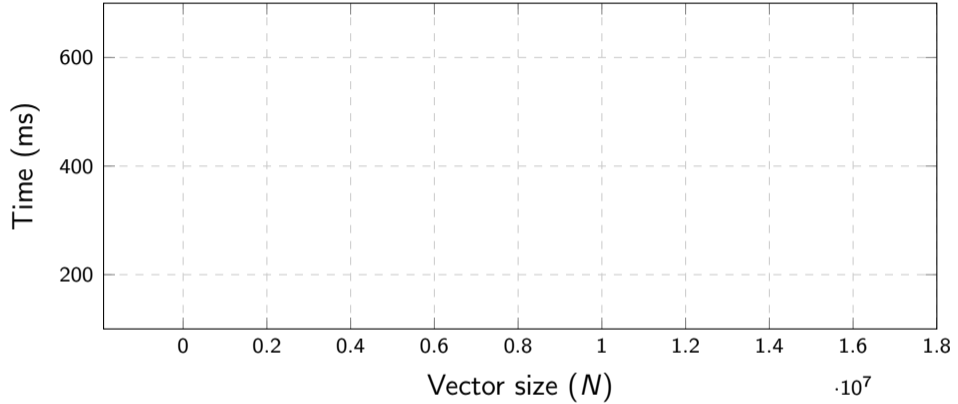
0, 1, 2, \dots $i, i + 1, \dots$ $2i, 2i + 1, \dots \dots$ $N - 1$



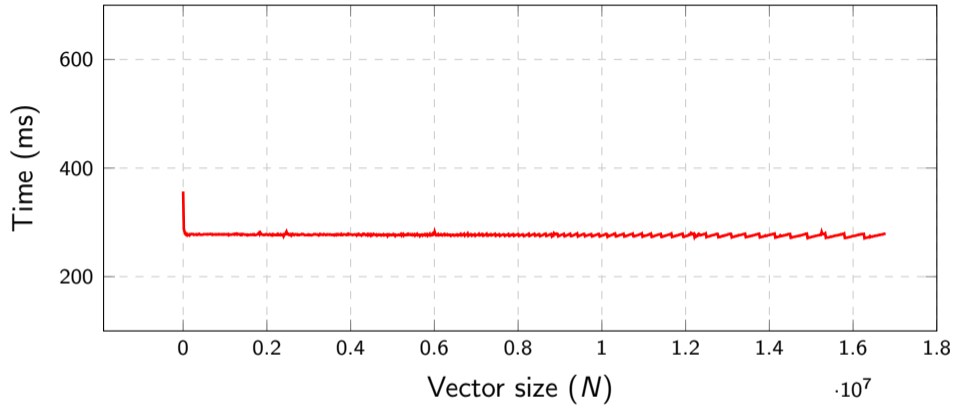




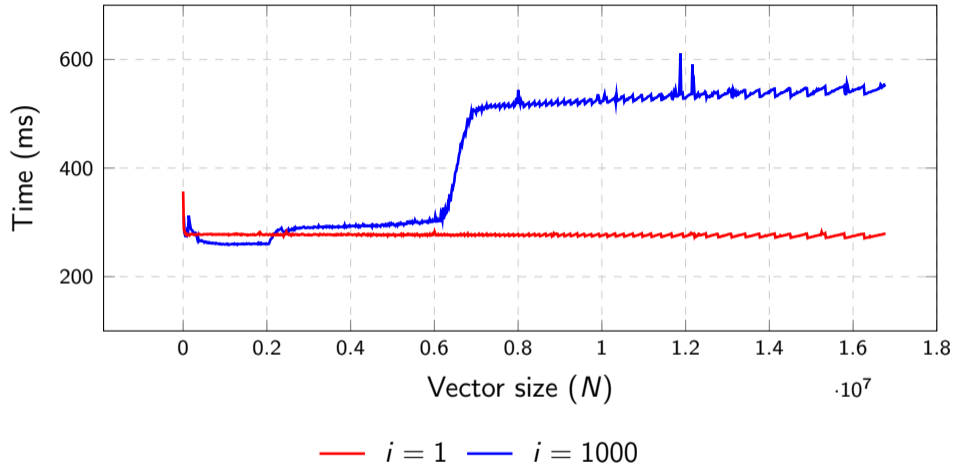


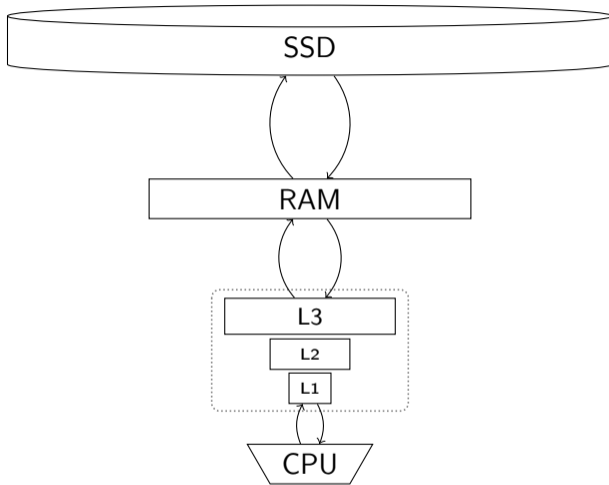


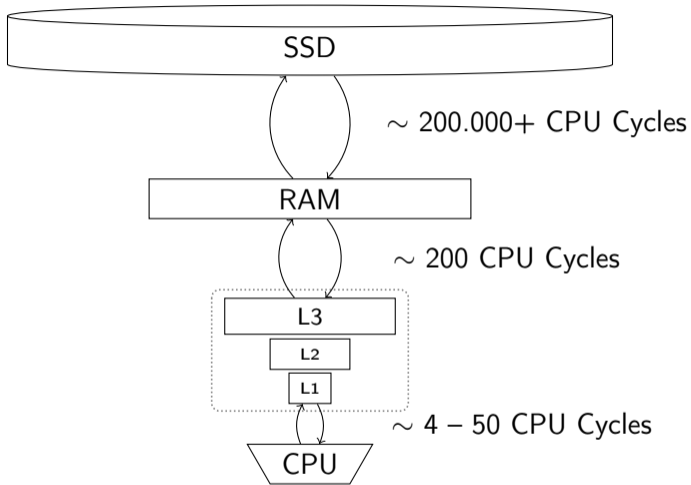
— $i = 1$ — $i = 1000$

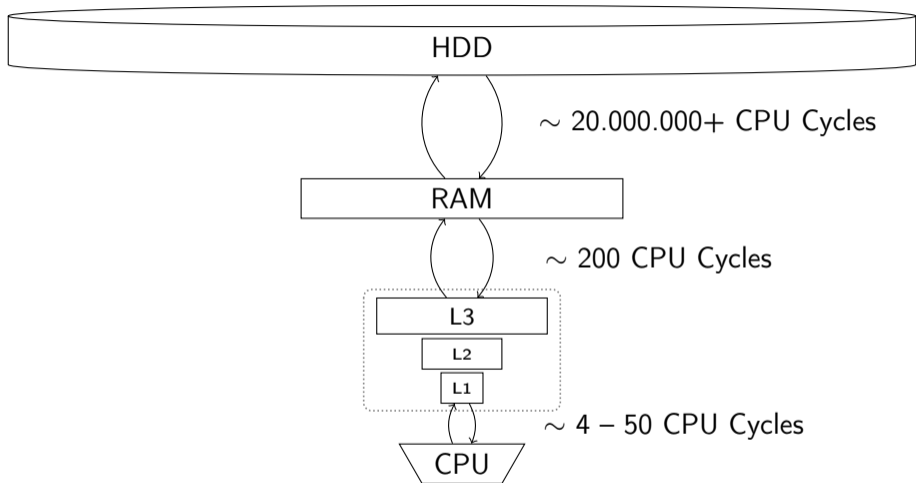


— $i = 1$ — $i = 1000$



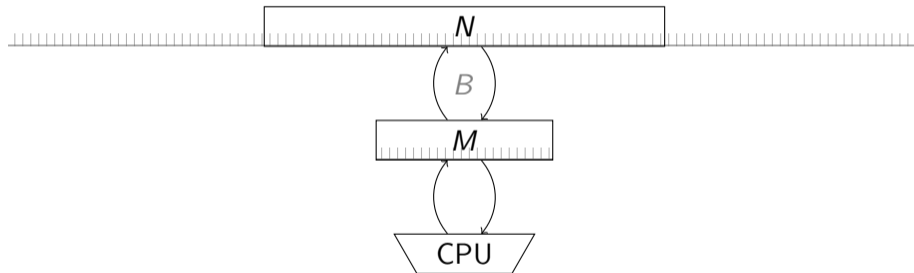






I/O Model

Aggarwal and Vitter '87



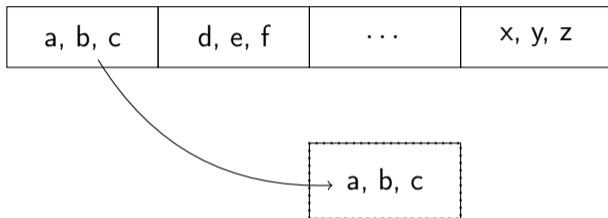
I/O Model : Sequential Access

Aggarwal and Vitter '87



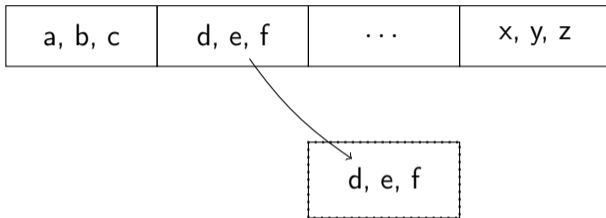
I/O Model : Sequential Access

Aggarwal and Vitter '87



I/O Model : Sequential Access

Aggarwal and Vitter '87



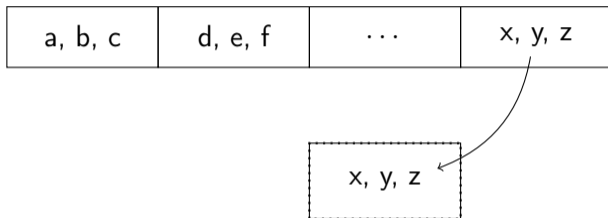
I/O Model : Sequential Access

Aggarwal and Vitter '87



I/O Model : Sequential Access

Aggarwal and Vitter '87



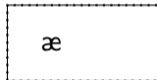
I/O Model : Sequential Access

Aggarwal and Vitter '87



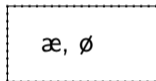
I/O Model : Sequential Access

Aggarwal and Vitter '87



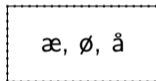
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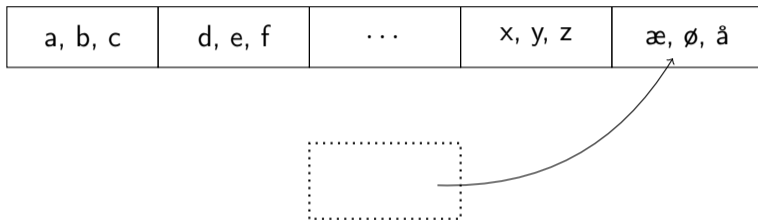
I/O Model : Sequential Access

Aggarwal and Vitter '87



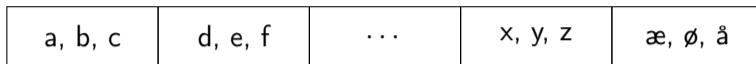
I/O Model : Sequential Access

Aggarwal and Vitter '87



I/O Model : Sequential Access

Aggarwal and Vitter '87

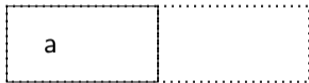


Time : N
I/O : N/B
Memory : B

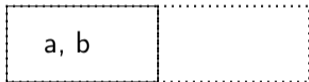
I/O Model : Stack



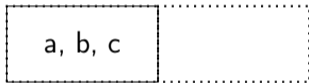
I/O Model : Stack



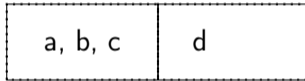
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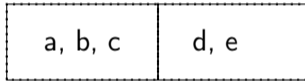
I/O Model : Stack



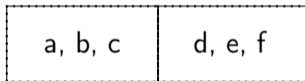
I/O Model : Stack



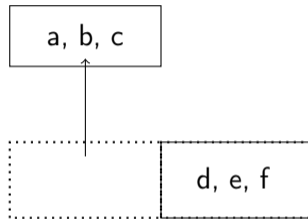
I/O Model : Stack



I/O Model : Stack



I/O Model : Stack



I/O Model : Stack

a, b, c

g	d, e, f
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I/O Model : Stack

a, b, c

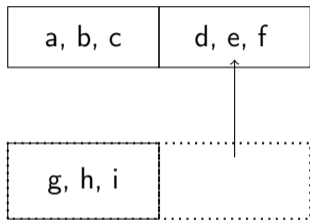
g, h	d, e, f
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I/O Model : Stack

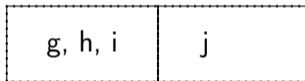
a, b, c

g, h, i | d, e, f

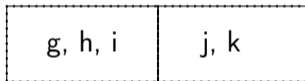
I/O Model : Stack



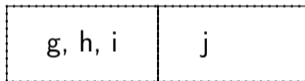
I/O Model : Stack



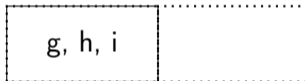
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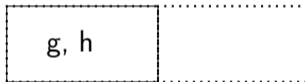
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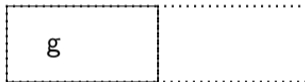
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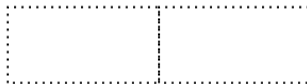
I/O Model : Stack



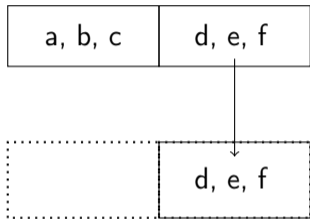
I/O Model : Stack



I/O Model : Stack



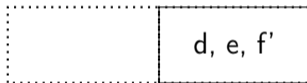
I/O Model : Stack



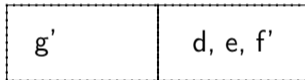
I/O Model : Stack



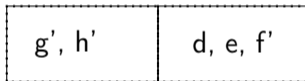
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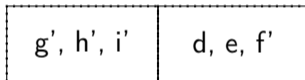
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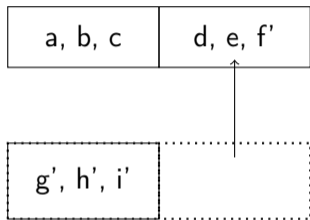
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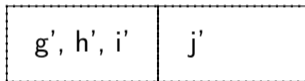
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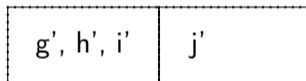
I/O Model : Stack



I/O Model : Stack



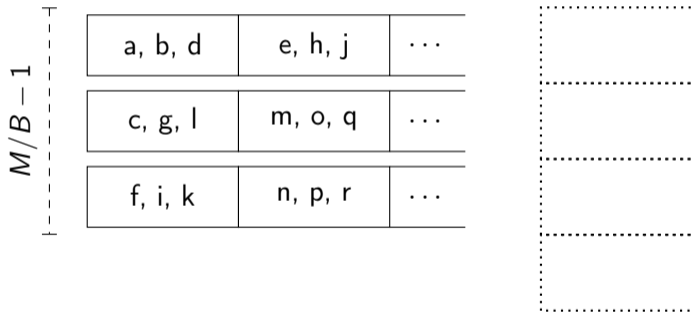
I/O Model : Stack



Time : $O(N)$
I/O : $O(N/B)$
Memory : $2B$

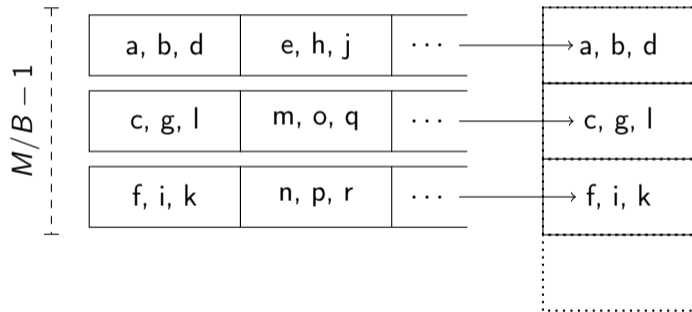
I/O Model : M/B-way Mergesort

Aggarwal and Vitter '87



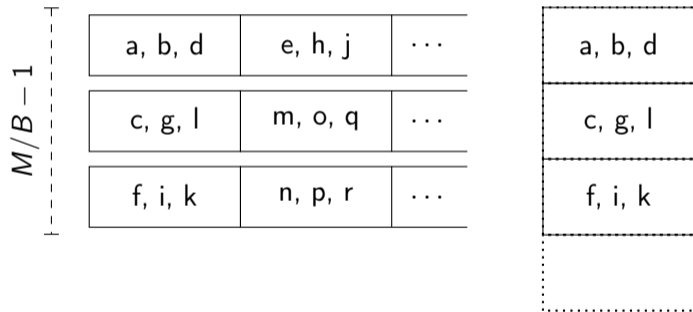
I/O Model : M/B-way Mergesort

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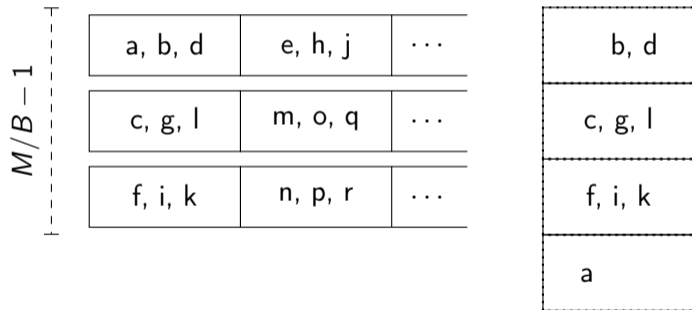
I/O Model : M/B-way Mergesort

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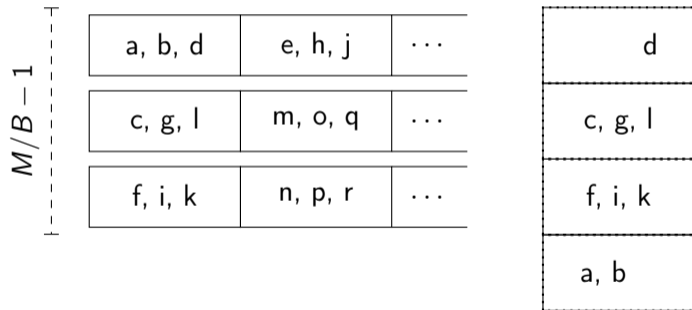
I/O Model : M/B-way Mergesort

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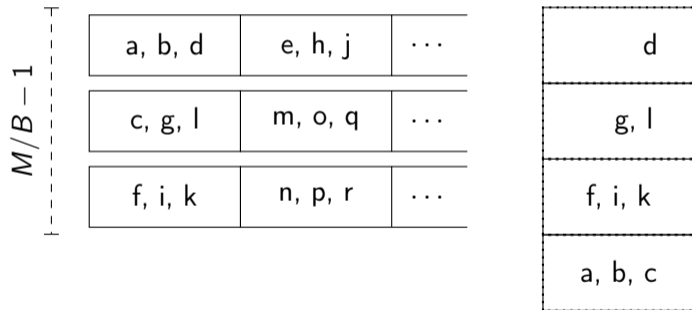
I/O Model : M/B-way Mergesort

Aggarwal and Vitter '87



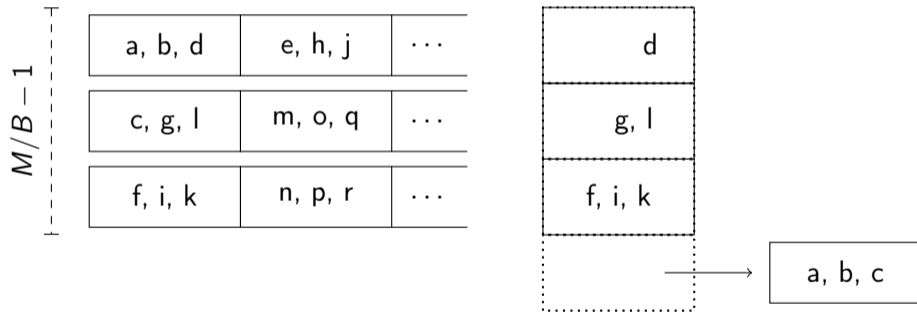
I/O Model : M/B-way Mergesort

Aggarwal and Vitter '87

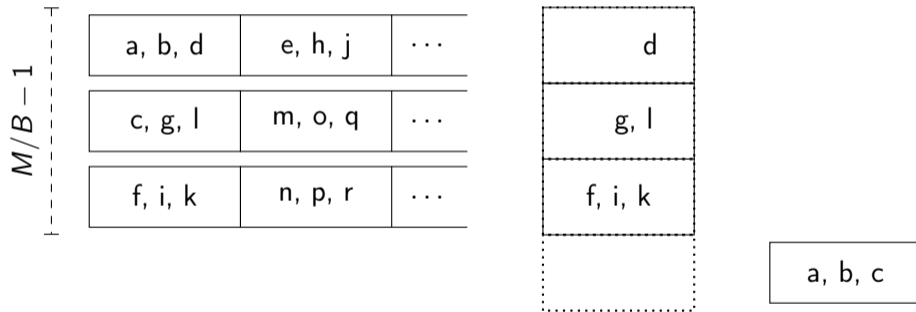


I/O Model : M/B-way Mergesort

Aggarwal and Vitter '87

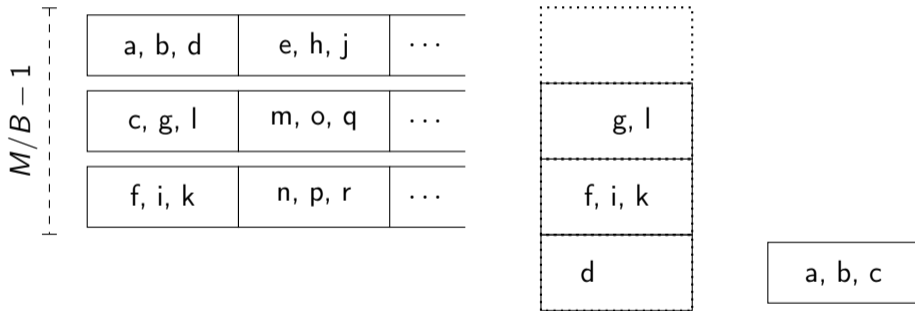


I/O Model : M/B-way Mergesort Aggarwal and Vitter '87



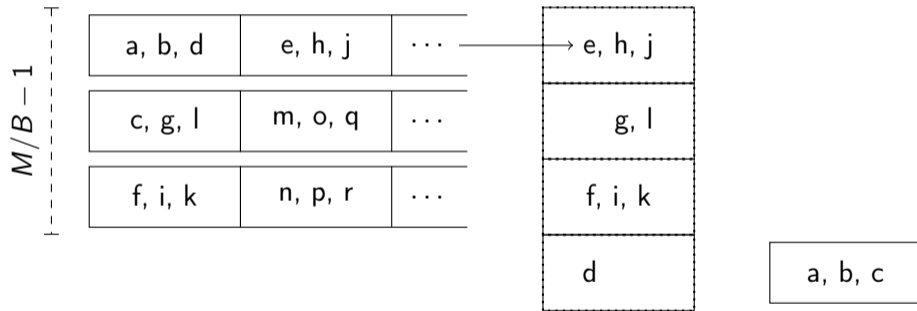
I/O Model : M/B-way Mergesort

Aggarwal and Vitter '87



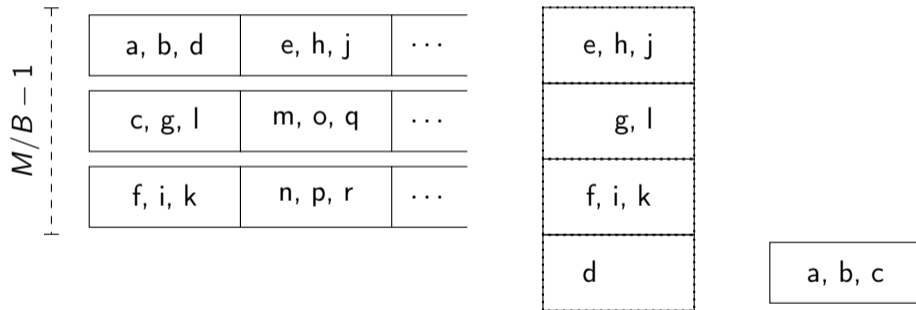
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Aggarwal and Vitter '87



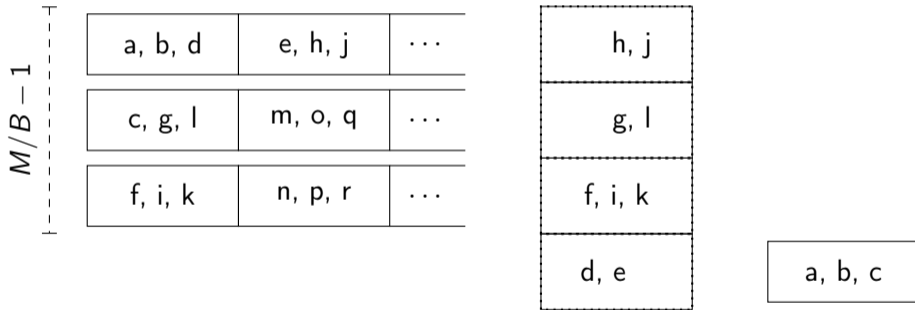
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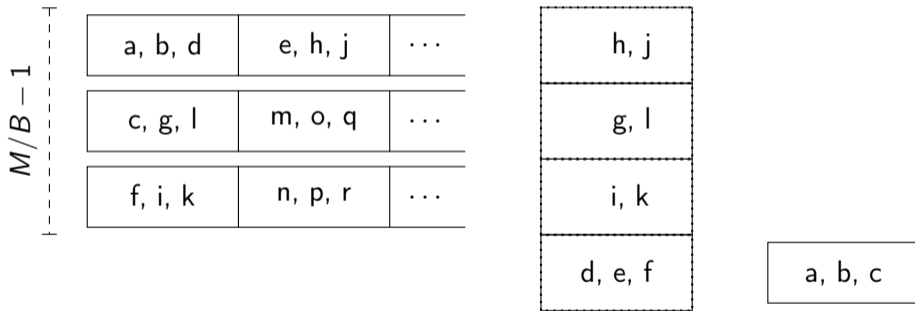
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Aggarwal and Vitter '87



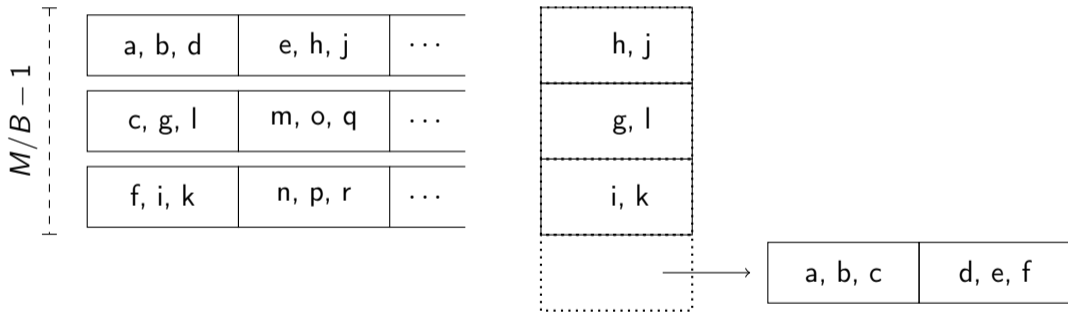
I/O Model : M/B-way Mergesort

Aggarwal and Vitter '87



I/O Model : M/B-way Mergesort

Aggarwal and Vitter '87



I/O Model : M/B-way Mergesort

Aggarwal and Vitter '87

I/O Model : M/B-way Mergesort

Aggarwal and Vitter '87

B

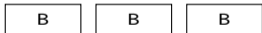
I/O Model : M/B-way Mergesort

Aggarwal and Vitter '87



I/O Model : M/B-way Mergesort

Aggarwal and Vitter '87



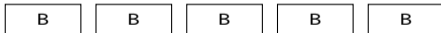
I/O Model : M/B-way Mergesort

Aggarwal and Vitter '87



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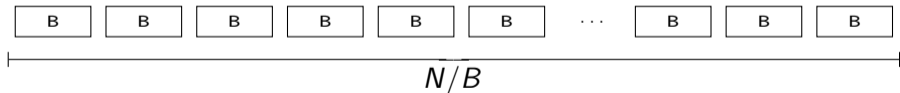
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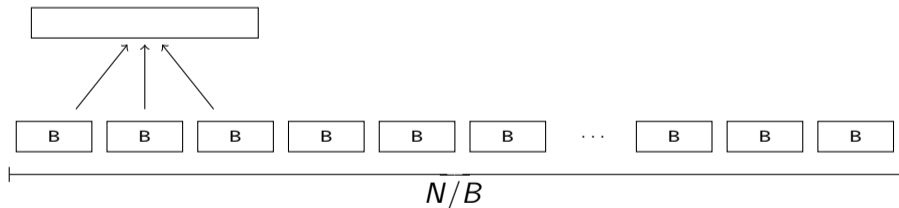
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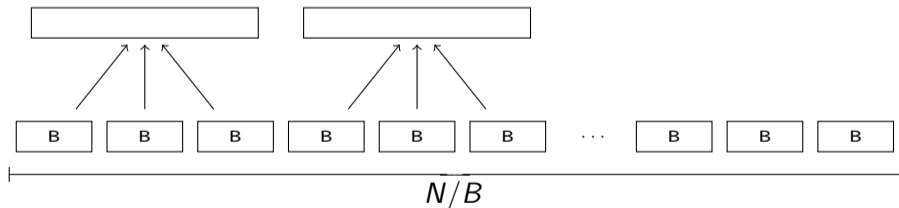
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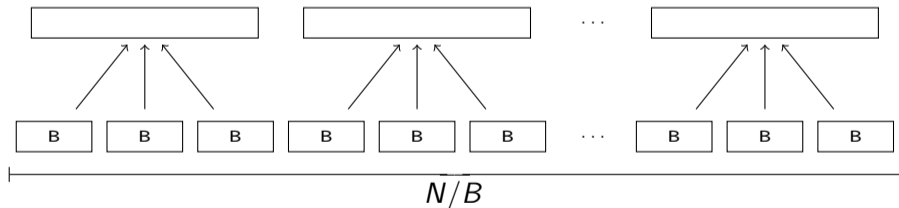
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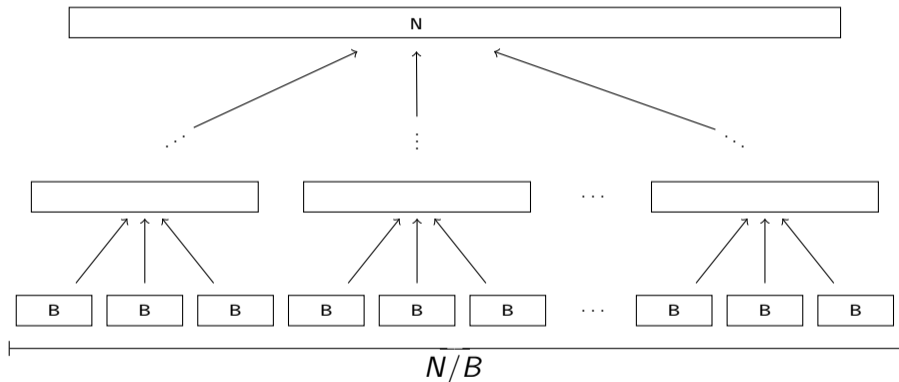
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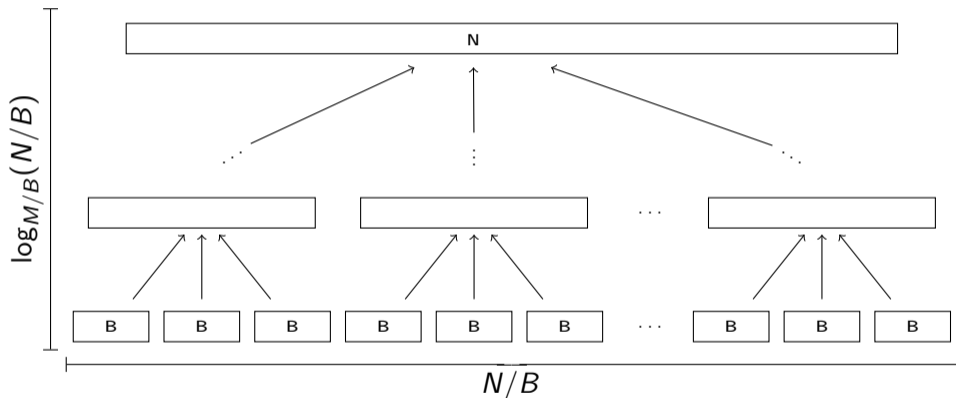
I/O Model : M/B-way Mergesort

Aggarwal and Vitter '87



I/O Model : M/B-way Mergesort

Aggarwal and Vitter '87



I/O Model : M/B-way Mergesort

Aggarwal and Vitter '87

Theorem

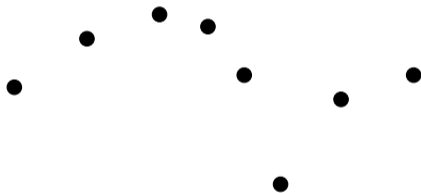
N elements can be sorted in $\Theta(N/B \cdot \log_{M/B}(N/B))$ I/Os.

Convex Hull : Graham Scan

Graham '72

Convex Hull

Compute the *convex hull* for N points in the plane.



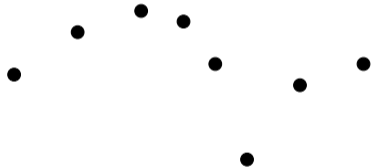
Theorem

Convex Hull can be computed in $O(N/B \cdot \log_{M/B}(N/B))$ I/Os.

Convex Hull : Graham Scan

Graham '72

Upper Hull:

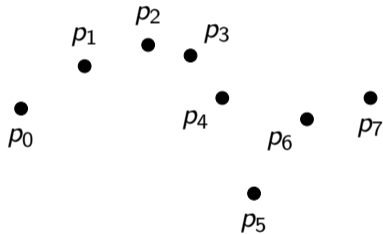


Convex Hull : Graham Scan

Graham '72

Upper Hull:

- Sort input points by x -axis

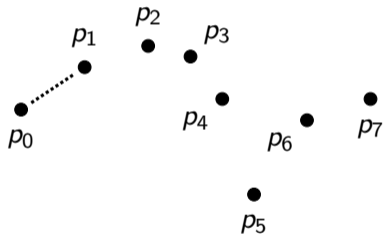


Convex Hull : Graham Scan

Graham '72

Upper Hull:

- Sort input points by x -axis
- Initialize stack $S = [p_0, p_1]$

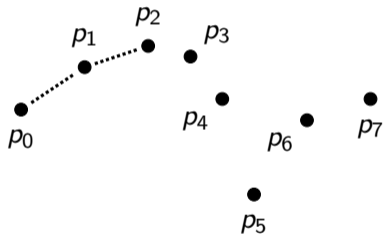


Convex Hull : Graham Scan

Graham '72

Upper Hull:

- Sort input points by x -axis
- Initialize stack $S = [p_0, p_1]$
- For remaining points $p_i \in p_2, p_3, \dots, p_{N-1}$:
 - 1 Let p_s, p_t be the two top-most points of S
 - 2 While $p_s - p_t - p_i$ is a “left-turn”:
 - Pop p_t and go-to 1
 - 3 Push p_i onto S

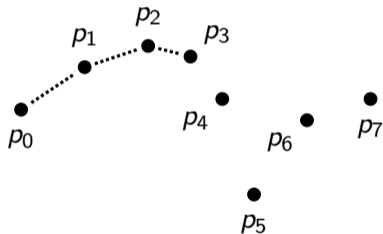


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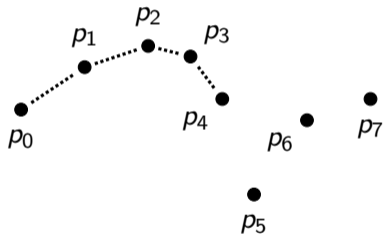


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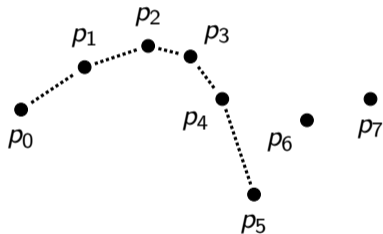


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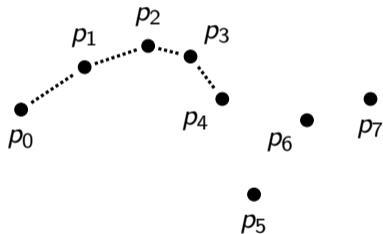


Convex Hull : Graham Scan

Graham '72

Upper Hull:

- Sort input points by x -axis
- Initialize stack $S = [p_0, p_1]$
- For remaining points $p_i \in p_2, p_3, \dots, p_{N-1}$:
 - 1 Let p_s, p_t be the two top-most points of S
 - 2 While $p_s - p_t - p_i$ is a "left-turn":
 - Pop p_t and go-to 1
 - 3 Push p_i onto S

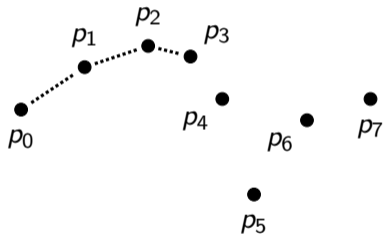


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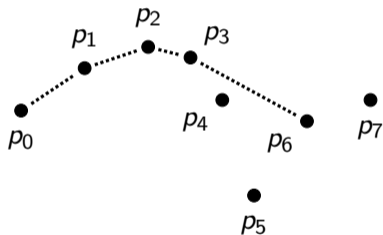


Convex Hull : Graham Scan

Graham '72

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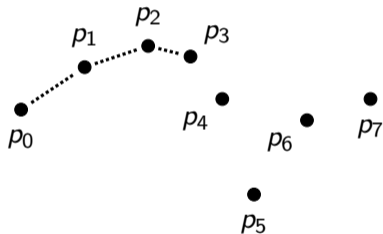


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 - 3 Push p_i onto S

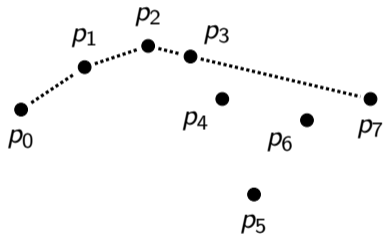


Convex Hull : Graham Scan

Graham '72

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Convex Hull : Graham Scan

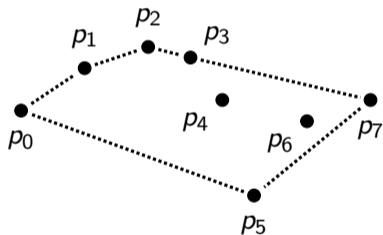
Graham '72

Upper Hull:

- Sort input points by x -axis
- Initialize stack $S = [p_0, p_1]$
- For remaining points $p_i \in p_2, p_3, \dots, p_{N-1}$:
 - 1 Let p_s, p_t be the two top-most points of S
 - 2 While $p_s - p_t - p_i$ is a “left-turn”:
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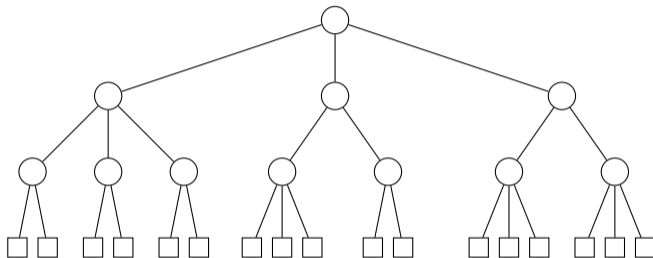
Lower Hull:

- Symmetric...



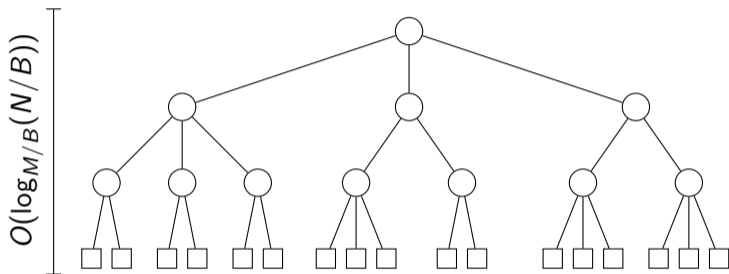
a-b Tree

Huddleston and Mehlhorn '82



Buffer Tree

Arge '95



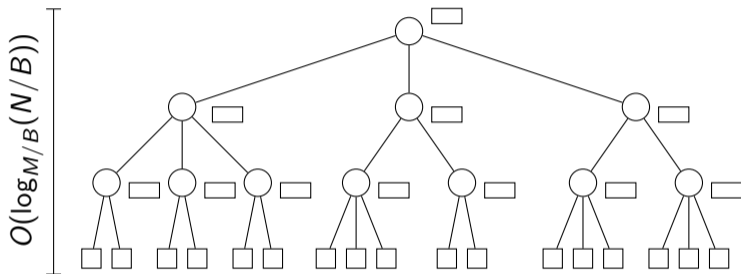
$$a = \frac{1}{4}M/B,$$

$$b = M/B,$$

$$\text{Leaf Size} = B$$

Buffer Tree

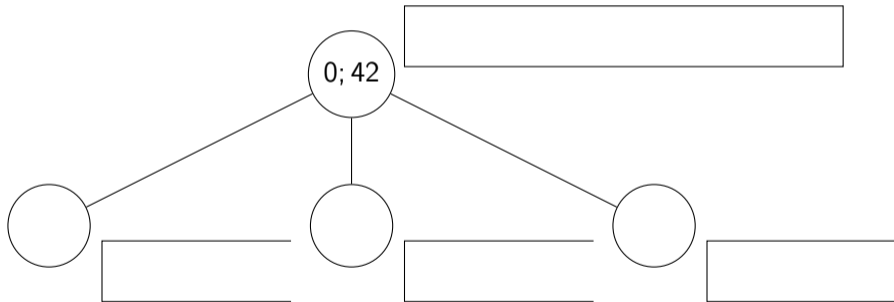
Arge '95



$$a = \frac{1}{4}M/B, \quad b = M/B, \quad \text{Leaf Size} = B$$

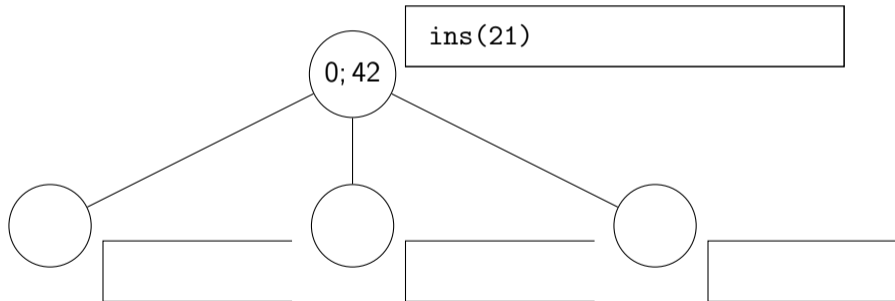
Buffer Tree

Arge '95



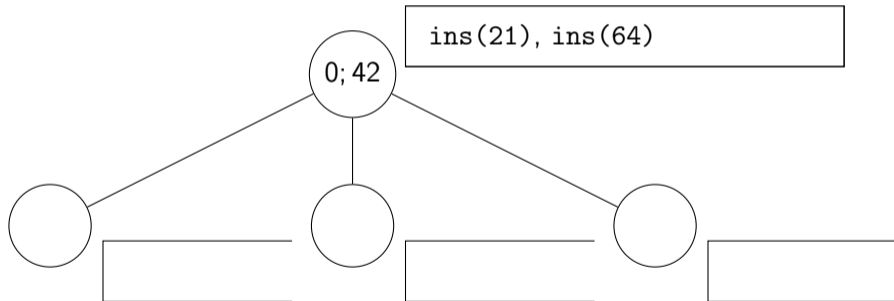
Buffer Tree

Arge '95



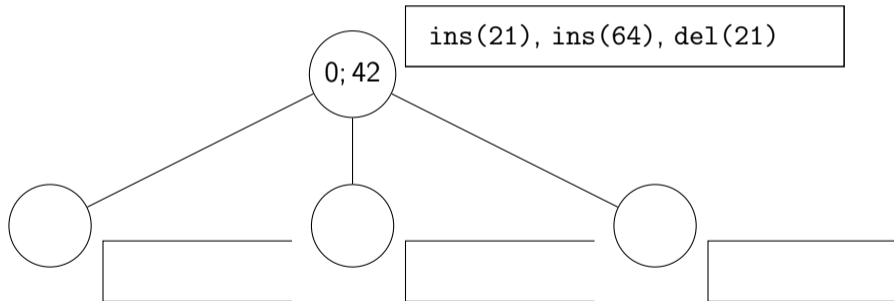
Buffer Tree

Arge '95



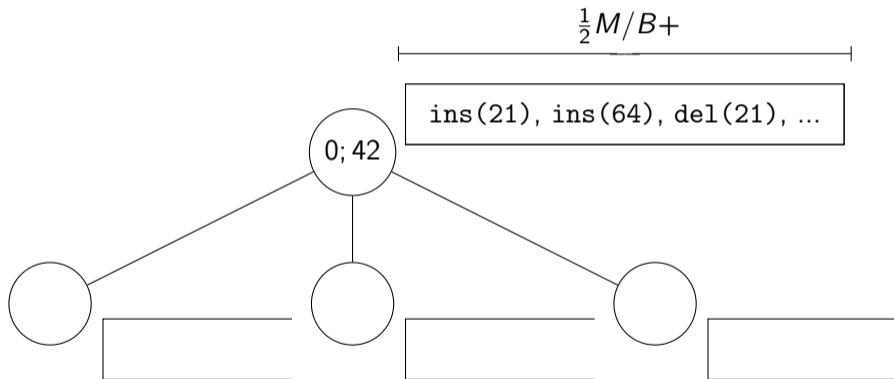
Buffer Tree

Arge '95



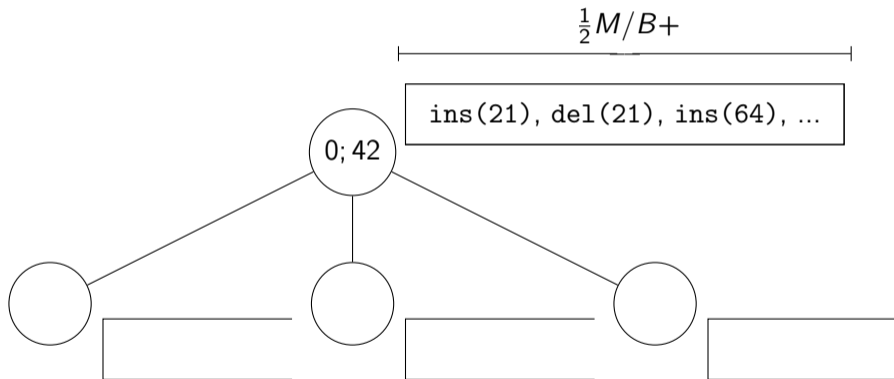
Buffer Tree

Arge '95



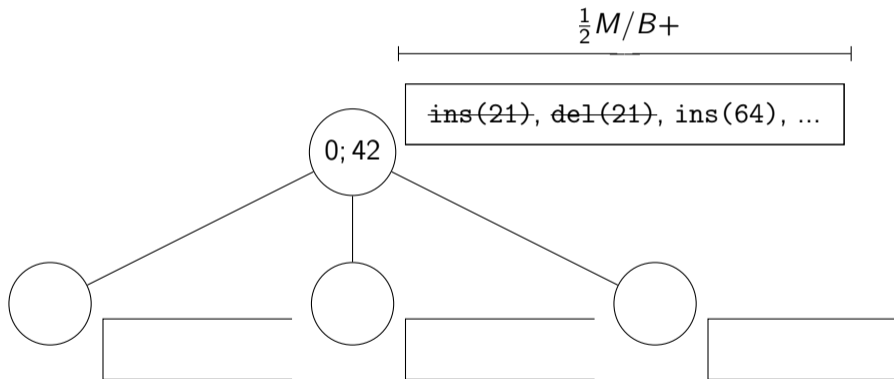
Buffer Tree

Arge '95



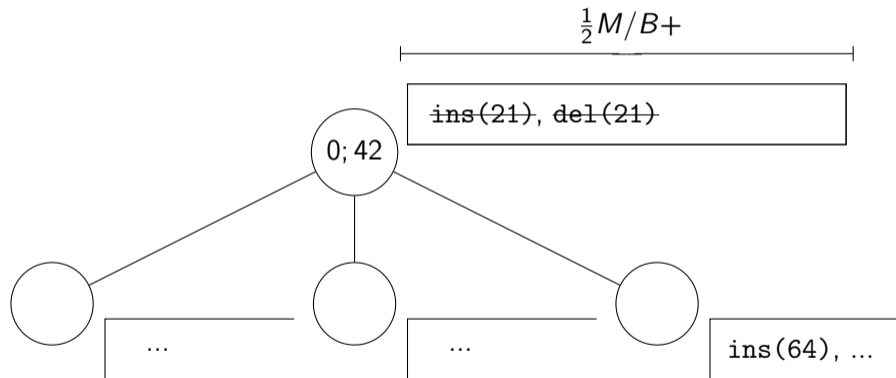
Buffer Tree

Arge '95



Buffer Tree

Arge '95



Buffer Tree

Arge '95

Theorem

A Buffer Tree can resolve N inserts and deletes in $\Theta(N/B \cdot \log_{M/B}(N/B))$ I/Os.

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A Buffer Tree with N requests can empty all its buffers, and output all remaining sorted elements, in $\Theta(N/B)$ I/Os.

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Theorem

A Buffer Tree with N requests can empty all its buffers, and output all remaining sorted elements, in $\Theta(N/B)$ I/Os.

Corollary

An I/O-efficient Priority Queue can resolve N push and delete min operations in $\Theta(N/B \cdot \log_{M/B}(N/B))$ I/Os.

Proof.

Use an $M/2$ sized internal memory priority queue, pq. If pq overflows, move $M/4$ the largest elements to a Buffer Tree, t. If pq underflows, obtain the $M/4$ smallest elements from t. \square

Binary Decision Diagrams

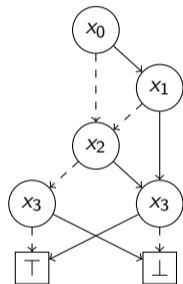
Arge '96, Sølvsten '22

#Paths

Given a Binary Decision Diagram of N nodes, compute the number of paths from the root to the \top terminal.

Theorem

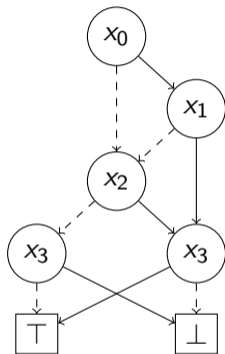
#Paths can be computed in $O(N/B \cdot \log_{M/B}(N/B))$ I/Os.



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

Binary Decision Diagrams

Arge '96, Sølvsten '22



Decision Diagram

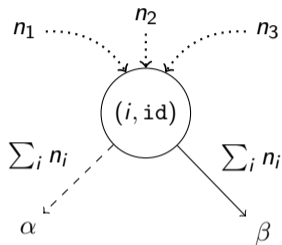
[((0, 0), (2, 0), (1, 0)) ,
((1, 0), (2, 0), (3, 1)) ,
((2, 0), (3, 0), (3, 1)) ,
((3, 0), T, ⊥) ,
((3, 1), ⊥, T)]

On-Disk Format

(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

Binary Decision Diagrams

Arge '96, Sølvsten '22

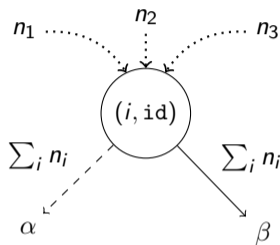


Idea

Count the number of in-going paths to each node.

Binary Decision Diagrams

Arge '96, Sølvsten '22



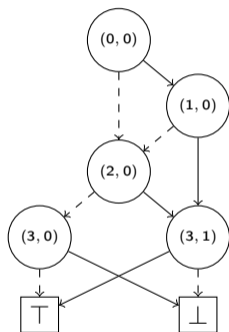
Time-Forward Processing

Defer work with $Q_{count} : \text{PriorityQueue}\langle (s \rightarrow t, \mathbb{N}) \rangle$ sorted on t in ascending order.

$$((i, id) \stackrel{\perp}{\rightarrow} \alpha, \sum_i n_i), \quad ((i, id) \stackrel{\top}{\rightarrow} \beta, \sum_i n_i)$$

Binary Decision Diagrams

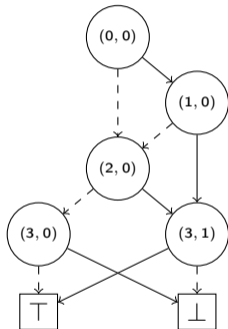
Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

Binary Decision Diagrams

Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

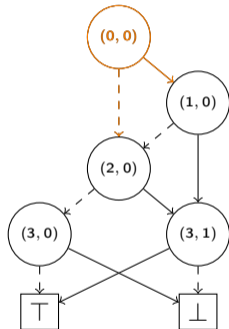
Priority Queue: Q_{count} :

[

]

Binary Decision Diagrams

Arge '96, Sølvsten '22



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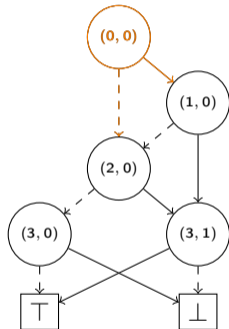
Priority Queue: Q_{count} :

[

]

Binary Decision Diagrams

Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

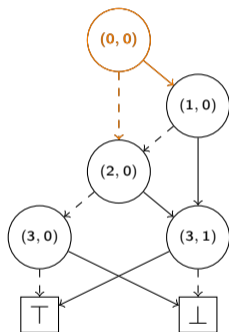
Priority Queue: Q_{count} :

[$((0, 0) \xrightarrow{\top} (1, 0), 1)$,
 $((0, 0) \xrightarrow{\perp} (2, 0), 1)$,

]

Binary Decision Diagrams

Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

Seek	Sum	Result
(1, 0)	0	0

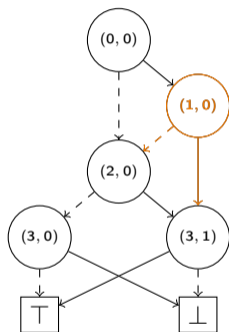
Priority Queue: Q_{count} :

[$((0, 0) \xrightarrow{T} (1, 0), 1)$,
 $((0, 0) \xrightarrow{\perp} (2, 0), 1)$,

]

Binary Decision Diagrams

Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

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(1, 0)	0	0

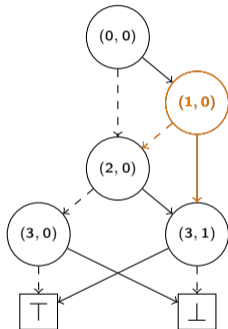
Priority Queue: Q_{count} :

[$((0,0) \xrightarrow{T} (1,0), 1)$,
 $((0,0) \xrightarrow{\perp} (2,0), 1)$,

]

Binary Decision Diagrams

Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

Seek	Sum	Result
(1, 0)	1	0

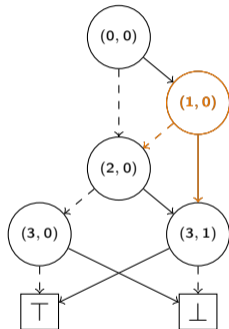
Priority Queue: Q_{count} :

[
((0, 0) $\stackrel{\perp}{\rightarrow}$ (2, 0), 1) ,

]

Binary Decision Diagrams

Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

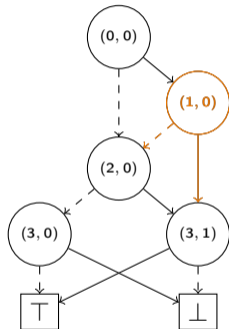
Seek	Sum	Result
(1, 0)	1	0

Priority Queue: Q_{count} :

[
	$((0, 0) \xrightarrow{\perp} (2, 0), 1)$,	
	$((1, 0) \xrightarrow{\perp} (2, 0), 1)$,	
	$((1, 0) \xrightarrow{\top} (3, 1), 1)$,	
]

Binary Decision Diagrams

Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

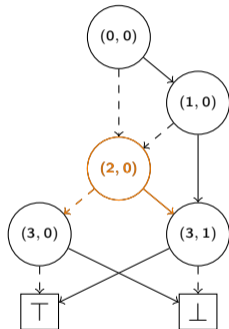
Seek	Sum	Result
(2, 0)	0	0

Priority Queue: Q_{count} :

[
	$((0, 0) \stackrel{\perp}{\rightarrow} (2, 0), 1)$,	
	$((1, 0) \stackrel{\perp}{\rightarrow} (2, 0), 1)$,	
	$((1, 0) \stackrel{\top}{\rightarrow} (3, 1), 1)$,	
]

Binary Decision Diagrams

Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

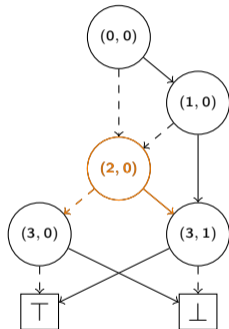
Seek	Sum	Result
(2, 0)	0	0

Priority Queue: Q_{count} :

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	$((0, 0) \stackrel{\perp}{\rightarrow} (2, 0), 1)$,	
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]

Binary Decision Diagrams

Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

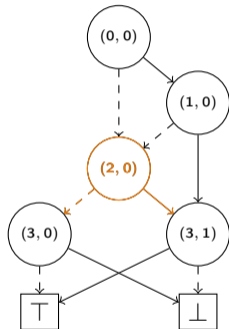
Seek	Sum	Result
(2, 0)	1	0

Priority Queue: Q_{count} :

[
((1, 0) $\stackrel{\perp}{\rightarrow}$ (2, 0), 1) ,
((1, 0) $\stackrel{\top}{\rightarrow}$ (3, 1), 1) ,
]

Binary Decision Diagrams

Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

Seek	Sum	Result
(2, 0)	2	0

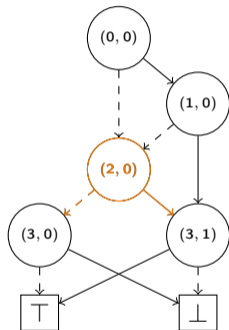
Priority Queue: Q_{count} :

[

$((1, 0) \xrightarrow{T} (3, 1), 1)$,
]

Binary Decision Diagrams

Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

Seek	Sum	Result
(2, 0)	2	0

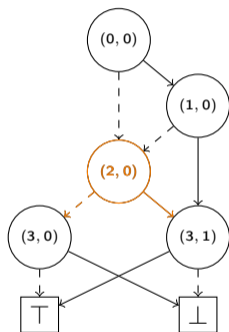
Priority Queue: Q_{count} :

[

$((2, 0) \xrightarrow{\perp} (3, 0), 2)$,
 $((1, 0) \xrightarrow{\top} (3, 1), 1)$,
 $((2, 0) \xrightarrow{\top} (3, 1), 2)$]

Binary Decision Diagrams

Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

Seek	Sum	Result
(3, 0)	0	0

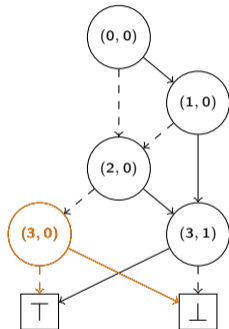
Priority Queue: Q_{count} :

[

$((2, 0) \xrightarrow{\perp} (3, 0), 2)$,
 $((1, 0) \xrightarrow{\top} (3, 1), 1)$,
 $((2, 0) \xrightarrow{\top} (3, 1), 2)$]

Binary Decision Diagrams

Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

Seek	Sum	Result
(3, 0)	0	0

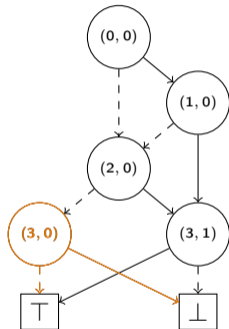
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[

$((2, 0) \xrightarrow{\perp} (3, 0), 2)$,
 $((1, 0) \xrightarrow{\top} (3, 1), 1)$,
 $((2, 0) \xrightarrow{\top} (3, 1), 2)$]

Binary Decision Diagrams

Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

Seek	Sum	Result
(3, 0)	2	0

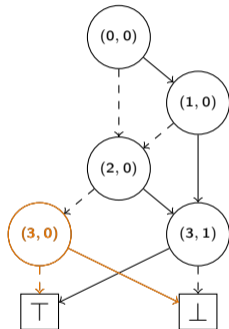
Priority Queue: Q_{count} :

[

$((1, 0) \xrightarrow{T} (3, 1), 1)$,
 $((2, 0) \xrightarrow{T} (3, 1), 2)$]

Binary Decision Diagrams

Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

Seek	Sum	Result
(3, 0)	2	2

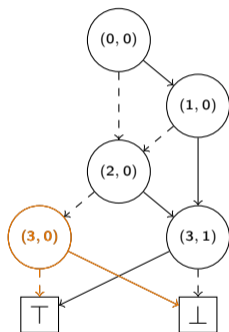
Priority Queue: Q_{count} :

[

$((1, 0) \xrightarrow{T} (3, 1), 1)$,
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Binary Decision Diagrams

Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

Seek	Sum	Result
(3, 1)	0	2

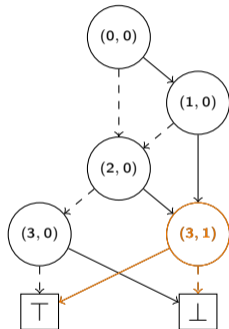
Priority Queue: Q_{count} :

[

$((1, 0) \xrightarrow{T} (3, 1), 1)$,
 $((2, 0) \xrightarrow{T} (3, 1), 2)$]

Binary Decision Diagrams

Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

Seek	Sum	Result
$(3, 1)$	0	2

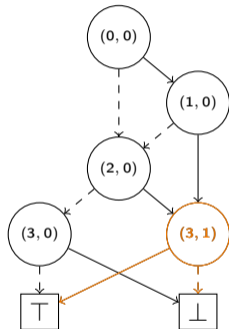
Priority Queue: Q_{count} :

[

$((1, 0) \xrightarrow{T} (3, 1), 1)$,
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Binary Decision Diagrams

Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

Seek	Sum	Result
(3, 1)	1	2

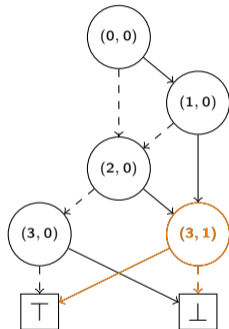
Priority Queue: Q_{count} :

[

$((2, 0) \xrightarrow{T} (3, 1), 2)$]

Binary Decision Diagrams

Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

Seek	Sum	Result
(3, 1)	3	2

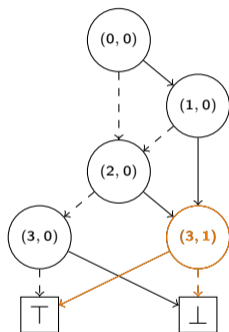
Priority Queue: Q_{count} :

[

]

Binary Decision Diagrams

Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

Seek	Sum	Result
(3, 1)	3	5

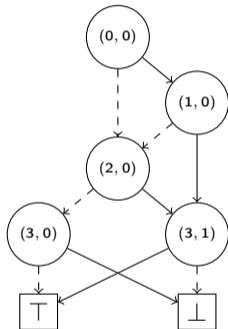
Priority Queue: Q_{count} :

[

]

Binary Decision Diagrams

Arge '96, Sølvsten '22



(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

Result

5

Priority Queue: Q_{count} :

[

]

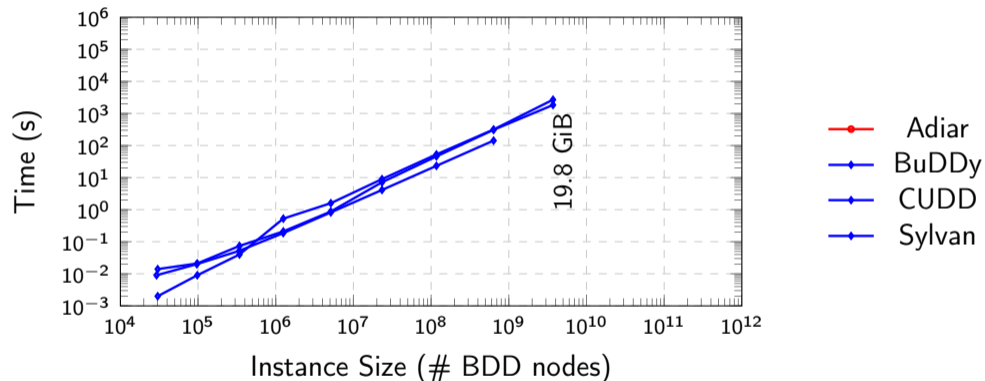
Adiar

I/O-efficient Decision Diagrams

github.com/ssoelvsten/adiar

Binary Decision Diagrams

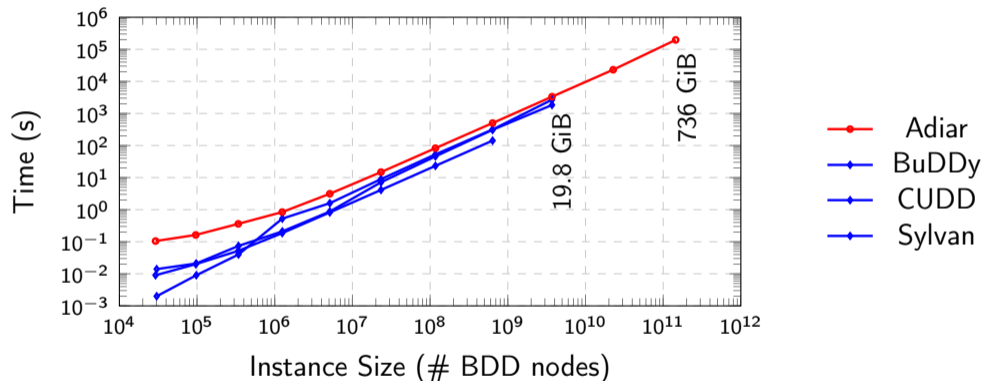
Arge '96, Sølvsten '22



Running time for the N -Queens problems.

Binary Decision Diagrams

Arge '96, Sølvsten '22



Running time for the *N-Queens* problems.

Further Reading : Foundations

- **Aggarwal and Vitter (1987)**

“The Input/Output Complexity of Sorting and Related Problems”

The I/O-model, Sorting, Permutation, FFT, and Matrix transposition.

- **Arge, Goodrich, Nelson, and Sitchinava (2008)**

“Fundamental Parallel Algorithms for Private-cache Chip Multiprocessors.”

The I/O-model for Multi-Threading.

Further Reading : Data Structures

- **Arge (1995)**

"The Buffer Tree: A new technique for Optimal I/O-algorithms"

An I/O-efficient Tree, Priority Queue, and Range Tree.

- **Sanders (2002)**

"Fast Priority Queues for Cached Memory"

A much faster I/O-efficient Priority Queue.

- **Agarwal, Arge and Yi (2006)**

"I/O-Efficient Batched Union-Find and Its Applications to Terrain Analysis"

An I/O-efficient (Lazy) Union-Find.

Further Reading : Algorithms

- **Goodrich, Tsay, Vengroff, and Vitter (1993)**

“External-Memory Computational Geometry”

Distribution Sweeping and other algorithms.

- **Chiang, Goodrich, Grove, Tamassia, Vengroff, and Vitter (1995)**

“External-memory Graph Algorithms”

Time-forward Processing and other algorithms.

- **Arge, Toma, Vitter (2001)**

“I/O-Efficient Algorithms for Problems on Grid-Based Terrains”

The TERRAFLOW algorithm.

Further Reading : Libraries (C++)

- **TPIE : Templated Portable I/O Environment**

`github.com/thomasmoelhave/tpie`

Duke University and Aarhus University

- **STXXL : Standard Template library for XXL data sets**

`github.com/stxxl/stxxl`

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Adiar

📄 github.com/ssoelvsten/adiar

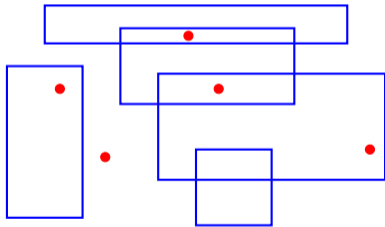
📖 ssoelvsten.github.io/adiar

Distribution Sweeping

Goodrich, Tsay, Vengroff, and Vitter '93

Batched Range Searching

Given N axis-parallel rectangles and N points in the plane, compute for each point p all rectangles containing p .



Theorem

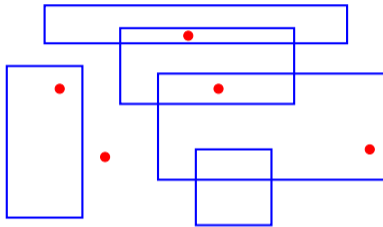
Batched Range Searching can be solved in $O(\text{sort}(N) + \text{scan}(T))$ I/Os.

Distribution Sweeping

Goodrich, Tsay, Vengroff, and Vitter '93

Preprocessing:

Algorithm:



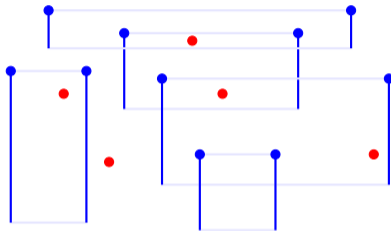
Distribution Sweeping

Goodrich, Tsay, Vengroff, and Vitter '93

Preprocessing:

- Split each rectangle into two vertical lines.

Algorithm:



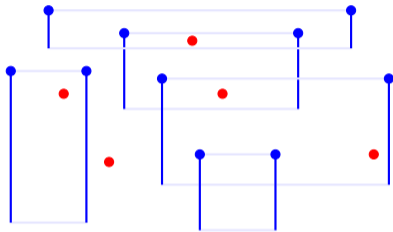
Distribution Sweeping

Goodrich, Tsay, Vengroff, and Vitter '93

Preprocessing:

- Split each rectangle into two vertical lines.
- Sort all lines and points by their x -value.

Algorithm:



Distribution Sweeping

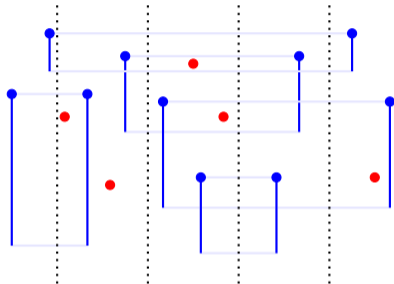
Goodrich, Tsay, Vengroff, and Vitter '93

Preprocessing:

- Split each rectangle into two vertical lines.
- Sort all lines and points by their x -value.

Algorithm:

- Split all data into $\Theta(\sqrt{M/B})$ slabs. Solve these recursively; output is given sorted by y -value.



Distribution Sweeping

Goodrich, Tsay, Vengroff, and Vitter '93

Preprocessing:

- Split each rectangle into two vertical lines.
- Sort all lines and points by their x -value.

Algorithm:

- Split all data into $\Theta(\sqrt{M/B})$ slabs. Solve these recursively; output is given sorted by y -value.
- Merge slabs together, report points between line segments outside its slab.
 - Use $\Theta(\sqrt{M/B^2}) = \Theta(\sqrt{M/B})$ multi-slabs to maintain each *active* rectangle.
 - Output points and un-matched line segments.

