

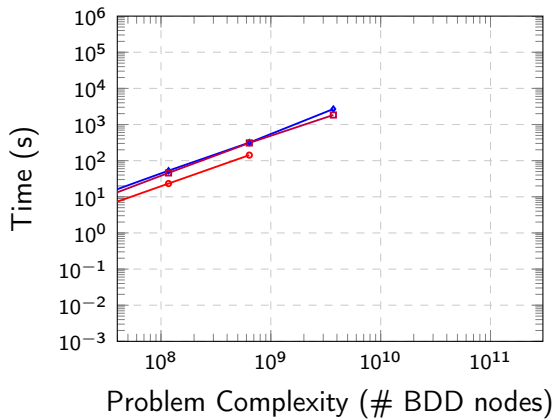
# Predicting Memory Demands of BDD Operations using Maximum Graph Cuts

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**Steffan Christ Sølvesten** and Jaco van de Pol

ATVA 2023





—○— BuDDy —◆— CUDD —■— Sylvan —●— Adiar v1.0

Running Time to solve  $N$ -Queens problems.



—○— BuDDy —◆— CUDD —□— Sylvan —●— Adiar v1.0

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## $i$ -level cut



# $i$ -level cut



**Lemma (Sølvsten, Van de Pol 2023)**  
*The maximum  $i$ -level cut problem is in  $P$  for  $i \in \{1, 2\}$ .*

**Theorem (Lampis, Kaouri, Mitsou 2011)**  
*The maximum  $i$ -level cut problem is NP-complete for  $i \geq 4$ .*



**Theorem (Sølvsten, Van de Pol 2023)**

Given maximum 2-level cuts size  $C_f$  for  $f$  and  $C_g$  for  $g$ , the maximum 2-level cut for  $f \odot g$  is less than or equal to  $C_f \cdot C_g$ .

**Proof.**



□

**Theorem (Sølvsten, Van de Pol 2023)**

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**Proof.**



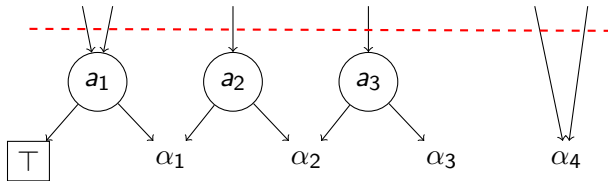
□



**Lemma (Sølvsten, Van de Pol 2023)**

*The maximum 2-level cut for  $f$  is at most  $\frac{3}{2}$  larger than its maximum 1-level cut.*

**Proof.**

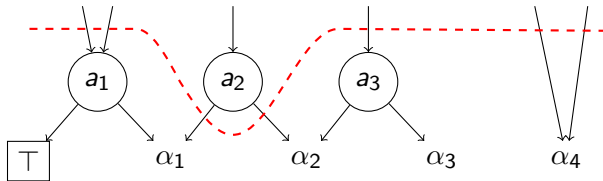


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□

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*The maximum 2-level cut for  $f$  is at most  $\frac{3}{2}$  larger than its maximum 1-level cut.*

**Proof.**



□





Overhead

Precision

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1-level cut	:	1.0%	69.2%
2-level cut	:	3.3%	86.3%



Possible to process a  
**1.1 GiB BDD**  
with only  
**128 MiB Memory**



Running Time

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Adiar v1.0 : 56.5 hours

Verification of the 15 smallest EPFL circuits.





### Running Time

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Adiar v1.0 : 56.5 hours

Adiar v1.2 : 4.0 hours (−93%)<sup>1</sup>

Verification of the 15 smallest EPFL circuits.

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<sup>1</sup> 52.1 of these hours were saved on just verifying the `sin` circuit alone.



# Steffan Christ Sølvsten

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











## Adiar

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🔗 [github.com/ssoelvsten/adiar](https://github.com/ssoelvsten/adiar)

📖 [ssoelvsten.github.io/adiar](https://ssoelvsten.github.io/adiar)



					
	Sufficient?	Overhead	Memory <sup>2</sup>	Disk R/W	Transition Cost
DF ▶ Adiar (  ▶  )	✗	3×	—	2×	—
DF    Adiar (      )	✓	—	3×	2×	—
DF → Adiar 1.0	✗ <sup>1</sup>	—	—	—	$\Omega(N \log N)$
State Pattern (  →  )	✓ <sup>4</sup>	$\sim 20\%$ <sup>3</sup>	2×	—	$\Omega(N)$
<i>i</i> -level cut (  /  )	✓ <sup>4</sup>	1%	—	—	—

Comparison of possible solutions.

<sup>1</sup>There can be a gap between when depth-first runs out of memory and Adiar 1.0 has no overhead.

<sup>2</sup>Decreasing the memory dedicated to an external memory data structure impacts its performance.

<sup>3</sup>Runtime polymorphism adds a 20% to 30% overhead [Stroustrup].

<sup>4</sup>This solves the gap<sup>1</sup>; a *non-trivial* integration with depth-first algorithms can cover tiny cases.



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



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Priority Queue:  $Q_{count}$ :

[

]



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

Priority Queue:  $Q_{count}$ :

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

]



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

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

Priority Queue:  $Q_{count}$ :

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

]



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

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]



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

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

Priority Queue:  $Q_{count}$ :

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

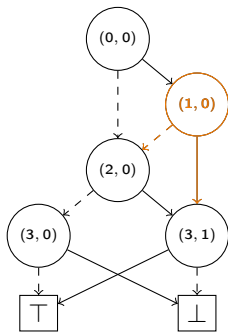


**(a)**  $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

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

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



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

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

Priority Queue:  $Q_{count}$ :

[  
 $((0, 0) \xrightarrow{\perp} (2, 0), 1)$  ,  
 $((1, 0) \xrightarrow{\perp} (2, 0), 1)$  ,  
 $((1, 0) \xrightarrow{\top} (3, 1), 1)$  ,  
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Seek	Sum	Result
<b>(2, 0)</b>	0	0

Priority Queue:  $Q_{count}$ :

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

]



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

Seek	Sum	Result
<b>(2, 0)</b>	1	0

Priority Queue:  $Q_{count}$ :

[

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

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

]





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

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

Priority Queue:  $Q_{count}$ :

[

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



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

Seek	Sum	Result
<b>(2, 0)</b>	2	0

Priority Queue:  $Q_{count}$ :

[

$((2, 0) \xrightarrow{\perp} (3, 0), 2)$  ,  
 $((1, 0) \xrightarrow{\top} (3, 1), 1)$  ,  
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<b>(3, 0)</b>	0	0

Priority Queue:  $Q_{count}$ :

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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	]



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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	]



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

Seek	Sum	Result
<b>(3, 0)</b>	2	0

Priority Queue:  $Q_{count}$ :

[

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



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

Seek	Sum	Result
<b>(3, 0)</b>	2	2

Priority Queue:  $Q_{count}$ :

[

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



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

Seek	Sum	Result
<b>(3, 1)</b>	0	2

Priority Queue:  $Q_{count}$ :

[

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





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

Seek	Sum	Result
(3, 1)	1	2

Priority Queue:  $Q_{count}$ :

[

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



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

Seek	Sum	Result
<b>(3, 1)</b>	3	2

Priority Queue:  $Q_{count}$ :

[

]



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

Seek	Sum	Result
<b>(3, 1)</b>	3	5

Priority Queue:  $Q_{count}$ :

[

]



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

Result  
5

Priority Queue:  $Q_{count}$ :

[

]

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