

I/O-efficient Manipulation of Binary Decision Diagrams

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Adiar: Binary Decision Diagrams in External Memory. 2022



Contents

What are Binary Decision Diagrams?

Why do they break?

How can we fix it?

- CountPaths

- Apply

- Equality Checking

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



(b) $\neg(x_0 \oplus x_2 \wedge x_3 : x_2 \wedge x_3)$

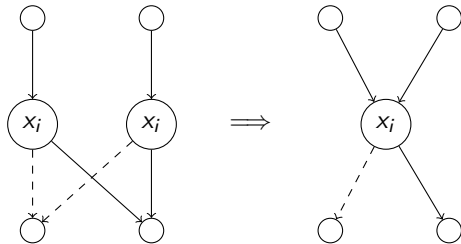
Examples of (Reduced Ordered) Binary Decision Diagrams.

Theorem (Bryant '86)

For a fixed variable order, if one exhaustively applies the two rules below, then one obtains the Reduced OBDD, which is a unique canonical form of the function.



(1) Remove redundant nodes



(2) Merge duplicate nodes

`bdd_apply(f,g, \odot)`

Base Case ($f, g \in \mathbb{B}$):



Inductive Case:



`bdd_apply(f,g,⊙)`

Base Case ($f, g \in \mathbb{B}$):



Inductive Case:



`bdd_apply(f,g,⊙)`

Let N_f , N_g be the size of the BDDs for f and g .

Let T be the $O(N_f \cdot N_g)$ size of the BDD for $f \odot g$.

Theorem

`bdd_apply(f,g,⊙)` runs in $O(N_f + N_g + T)$ time

- Memoisation (*Computation Cache*) ensures each (t_f, t_g) is only computed once.
- Reduction Rules can be maintained with a `make_node(i, t, e)` in $O(1)$ time.
 - 1 Redundancy is resolved with an if-statement.
 - 2 Duplication is avoided with a hash table (*Unique Node Table*).

Corollary

`bdd_apply(f,g,⊙)` runs in $O(1)$ time per BDD node.

Adiar

github.com/ssoelvsten/adiar



Running time of *BuDDy* for the *N*-Queens problem.



Running time of *BuDDy* for 3D Tic-Tac-Toe with $N = 21$.

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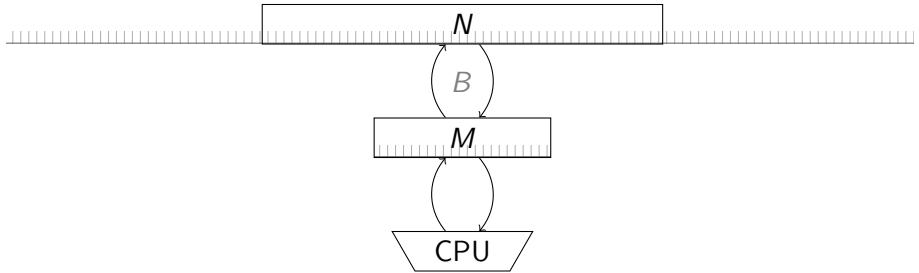
Apply

Equality Checking









The I/O model by Aggarwal and Vitter '87

For any realistic values of N , M , and B we have that

$$N/B < \text{sort}(N) \triangleq N/B \cdot \log_{M/B} N/B \ll N ,$$

Theorem (Aggarwal and Vitter '87)

N elements can be sorted in $\Theta(\text{sort}(N))$ I/Os.

Theorem (Arge '95)

A Priority Queue can do N insertions and extractions in $\Theta(\text{sort}(N))$ I/Os.

CountPaths : *Example*

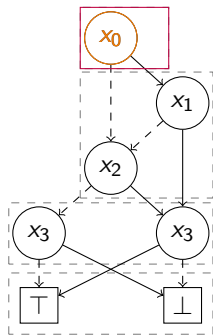


(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

$$M = 4, B = 2$$

node I/Os	cache lookups
0	0

CountPaths : *Example*



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

$$M = 4, B = 2$$

node I/Os	cache lookups
1	1

CountPaths : *Example*



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

$$M = 4, B = 2$$

node I/Os	cache lookups
2	2

CountPaths : *Example*



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

$$M = 4, B = 2$$

node I/Os	cache lookups
3	3

CountPaths : *Example*



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

$$M = 4, B = 2$$

node I/Os	cache lookups
4	3

CountPaths : *Example*

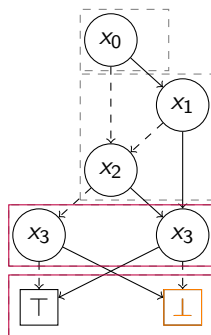


(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

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node I/Os	cache lookups
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CountPaths : *Example*



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$$M = 4, B = 2$$

node I/Os	cache lookups
4	3

CountPaths : *Example*



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

$$M = 4, B = 2$$

node I/Os	cache lookups
4	3

CountPaths : *Example*



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

$$M = 4, B = 2$$

node I/Os	cache lookups
5	3

CountPaths : *Example*



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

$$M = 4, B = 2$$

node I/Os	cache lookups
5	4

CountPaths : *Example*

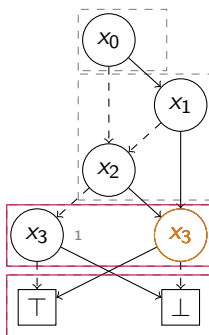


(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

$$M = 4, B = 2$$

node I/Os	cache lookups
6	4

CountPaths : *Example*

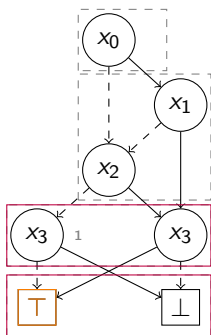


(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

$$M = 4, B = 2$$

node I/Os	cache lookups
6	4

CountPaths : *Example*



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

$$M = 4, B = 2$$

node I/Os	cache lookups
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CountPaths : *Example*



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

$$M = 4, B = 2$$

node I/Os	cache lookups
6	4

CountPaths : *Example*



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

$$M = 4, B = 2$$

node I/Os	cache lookups
7	4

CountPaths : *Example*



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

$$M = 4, B = 2$$

node I/Os	cache lookups
8	4

CountPaths : *Example*



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

$$M = 4, B = 2$$

node I/Os	cache lookups
8	6

CountPaths : *Example*

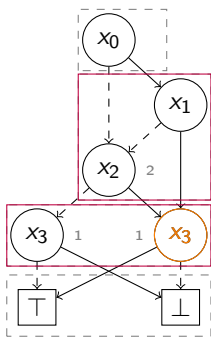


(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

$$M = 4, B = 2$$

node I/Os	cache lookups
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CountPaths : *Example*



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

$$M = 4, B = 2$$

node I/Os	cache lookups
9	7

CountPaths : *Example*



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

$$M = 4, B = 2$$

node I/Os	cache lookups
9	7

CountPaths : *Example*

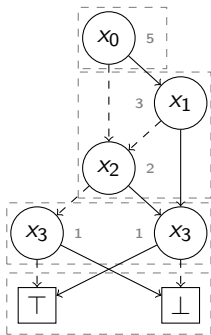


(a) $(x_0 \wedge x_1 \wedge x_3) \vee (x_2 \oplus x_3)$

$$M = 4, B = 2$$

node I/Os	cache lookups
10	7

CountPaths : *Example*



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

$$M = 4, B = 2$$

node I/Os	cache lookups
10	7

Algorithm	Time Complexity
bdd_pathcount	$O(N_f)$
bdd_not	$O(N_f)$
bdd_restrict	$O(N_f)$
bdd_apply	$O(N_f \cdot N_g)$
bdd_equal	$O(1)$

Algorithm	I/O-Complexity
bdd_pathcount	$O(N_f)$
bdd_not	$O(N_f)$
bdd_restrict	$O(N_f)$
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$$(i_1, id_1) < (i_2, id_2) \equiv i_1 < i_2 \vee (i_1 = i_2 \wedge id_i < id_j)$$



Node-based representation of prior shown BDDs

CountPaths



Idea

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

CountPaths



Time-Forward Processing

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

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

CountPaths : *Example*



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

CountPaths : *Example*



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

Priority Queue: Q_{count} :

[

]

CountPaths : *Example*



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

Priority Queue: Q_{count} :

[

]

CountPaths : *Example*



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

Priority Queue: Q_{count} :

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

]

CountPaths : *Example*



(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} :

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

]

CountPaths : *Example*



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

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]

CountPaths : *Example*



(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} :

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

]

CountPaths : *Example*



(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} :

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

CountPaths : *Example*



(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} :

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

CountPaths : *Example*



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

Seek	Sum	Result
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Priority Queue: Q_{count} :

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]

CountPaths : *Example*



(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} :

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

CountPaths : *Example*



(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} :

[

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

CountPaths : *Example*



(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} :

[

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

CountPaths : *Example*



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

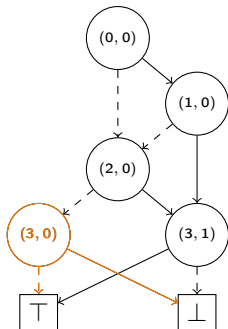
Seek	Sum	Result
(3, 0)	0	0

Priority Queue: Q_{count} :

[

$((2, 0) \xrightarrow{\perp} (3, 0), 2)$,
 $((1, 0) \xrightarrow{\top} (3, 1), 1)$,
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CountPaths : *Example*



(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} :

[

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

CountPaths : *Example*



(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} :

[

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

CountPaths : *Example*



(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} :

[

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

CountPaths : *Example*



(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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CountPaths : *Example*



(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} :

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

CountPaths : *Example*



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

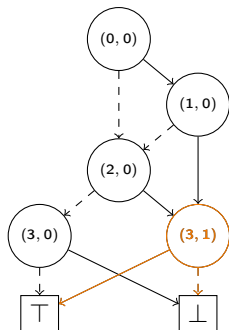
Seek	Sum	Result
(3, 1)	1	2

Priority Queue: Q_{count} :

[

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

CountPaths : *Example*



(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} :

[

]

CountPaths : *Example*



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

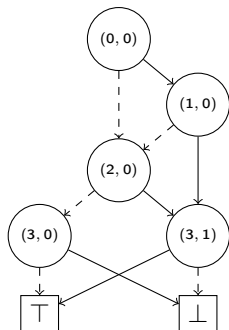
Seek	Sum	Result
(3, 1)	3	5

Priority Queue: Q_{count} :

[

]

CountPaths : *Example*



(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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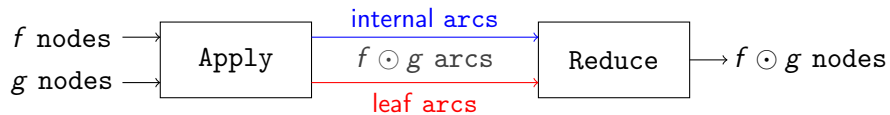
How can we fix it?

CountPaths

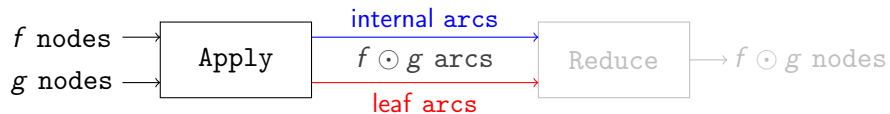
Apply

Equality Checking

Apply



Apply



Apply



Time-Forward Processing

Defer resolving products with $Q_{app:1}, Q_{app:2} : \text{PriorityQueue}\langle(s \rightarrow (t_f, t_g), \dots)\rangle$.

Apply



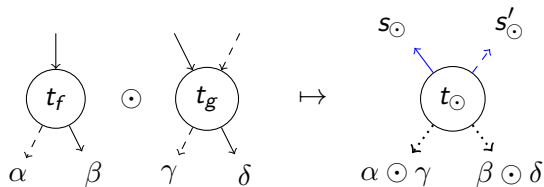
Observation (semi-transposition)

$\leftarrow : s \rightarrow t$ (Internal Arcs) are output at time t and hence sorted by t .

Time-Forward Processing

Defer resolving products with $Q_{app:1}, Q_{app:2} : \text{PriorityQueue}\langle (s \rightarrow (t_f, t_g), \dots) \rangle$.

Apply



Observation (semi-transposition)

$\leftarrow : s \rightarrow t$ (Internal Arcs) are output at time t and hence sorted by t .

Time-Forward Processing

Defer resolving products with $Q_{app:1}, Q_{app:2} : \text{PriorityQueue}\langle (s \rightarrow (t_f, t_g), \dots) \rangle$.

Apply



Observation (semi-tranposition)

$\leftarrow : s \rightarrow t$ (Internal Arcs) are output at time t and hence sorted by t .

$\rightarrow : s \rightarrow \mathbb{B}$ (Terminal Arcs) are output at time s .

Time-Forward Processing

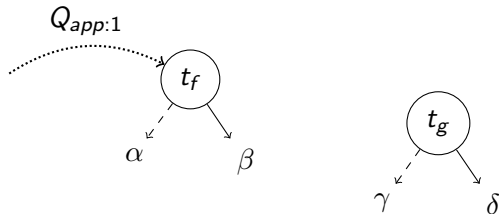
Defer resolving products with $Q_{app:1}, Q_{app:2} : \text{PriorityQueue}\langle (s \rightarrow (t_f, t_g), \dots) \rangle$.

Apply

$Q_{app:1}$: PriorityQueue $\langle (s \rightarrow (t_f, t_g)) \rangle$
sorted on $\min(t_f, t_g)$ in ascending order.

Case 1 :

$t_f.var() \neq t_g.var()$



Apply

$Q_{app:1}$: PriorityQueue $\langle(s \rightarrow (t_f, t_g))\rangle$
sorted on $\min(t_f, t_g)$ in ascending order.

Case 1 :

$$t_f.var() \neq t_g.var()$$



Case 2(a):

$$t_f.var() = t_g.var() \wedge t_f.id() = t_g.id()$$

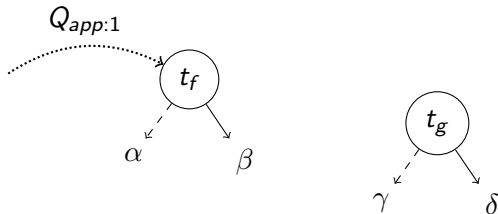


Apply

$Q_{app:1}$: PriorityQueue $\langle (s \rightarrow (t_f, t_g)) \rangle$
sorted on $\min(t_f, t_g)$ in ascending order.

Case 1 :

$$t_f.var() \neq t_g.var()$$



$Q_{app:2}$: PriorityQueue $\langle (s \rightarrow (t_f, t_g), (\alpha, \beta)) \rangle$
sorted on $\max(t_f, t_g)$ in ascending order.

Case 2(a):

$$t_f.var() = t_g.var() \wedge t_f.id() = t_g.id()$$

Case 2(b):

$$t_f.var() = t_g.var() \wedge t_f.id() \neq t_g.id()$$



Apply : *Example*



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

(c) $(a) \wedge (b)$

Apply : *Example*



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

(c) $(a) \wedge (b)$

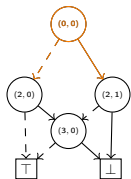
Apply : Example



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

Priority Queue: $Q_{app:1}$:

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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

]

(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:

$\min((1, 0), (2, 1))$

Priority Queue: $Q_{app:1}$:

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



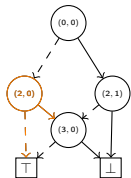
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(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:

$\min((1, 0), (2, 1))$

Priority Queue: $Q_{app:1}$:

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



]

(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:

$\min((1, 0), (2, 1))$

Priority Queue: $Q_{app:1}$:

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

]



(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\min((1, 0), (2, 1))$

Priority Queue: $Q_{app:1}$:

[

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

]

Output:
 $(0, 0) \xrightarrow{\top} (1, 0)$



(c) $(a) \wedge (b)$

Apply : Example



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



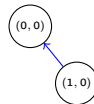
(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\min((2, 0), (2, 0))$

Priority Queue: $Q_{app:1}$:

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

Output:



(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\min((2, 0), (2, 0))$

Priority Queue: $Q_{app}:1$:

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

Output:



(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\min((2, 0), (2, 0))$

Priority Queue: $Q_{app:1}$:

[

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

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

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

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

Output:
 $(0, 0) \xrightarrow{\perp} (2, 0)$



(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\min((2, 0), (2, 1))$

Priority Queue: $Q_{app:1}$:

[

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

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

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

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

Output:



(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\min((2, 0), (2, 1))$

Priority Queue: $Q_{app:1}$:

[

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

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

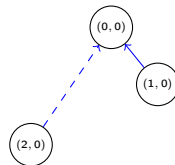
$(2, 0) \xrightarrow{\perp} ((3, 0), \top)$]

Priority Queue: $Q_{app:2}$:

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

]

Output:



(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\max((2, 0), (2, 1))$

Priority Queue: $Q_{app:1}$:

[

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

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

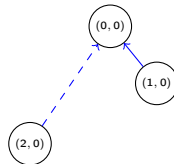
$(2, 0) \xrightarrow{\perp} ((3, 0), \top)$]

Priority Queue: $Q_{app:2}$:

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

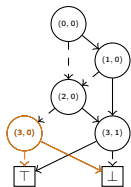
]

Output:

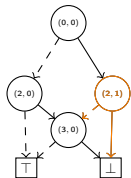


(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\max((2, 0), (2, 1))$

Priority Queue: $Q_{app:1}$:

[

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

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

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

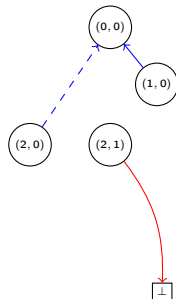
$(2, 0) \xrightarrow{\perp} ((3, 0), \top)$]

Priority Queue: $Q_{app:2}$:

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

]

Output:
 $(2, 1) \xrightarrow{\top} \perp$



(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\max((2, 0), (2, 1))$

Priority Queue: $Q_{app:1}$:

[

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

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

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

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

Priority Queue: $Q_{app:2}$:

[

]

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



(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\min((3, 1), (2, 1))$

Priority Queue: $Q_{app:1}$:

[

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

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

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

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

Priority Queue: $Q_{app:2}$:

[

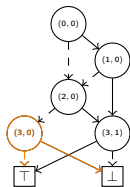
]

Output:

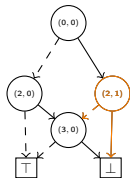


(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\min((3, 1), (2, 1))$

Priority Queue: $Q_{app:1}$:

[

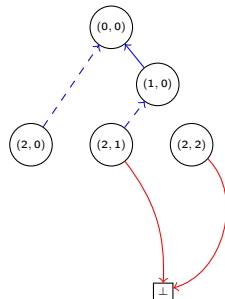
$(1, 0) \xrightarrow{\top} ((3, 1), (2, 1))$,
 $(2, 1) \xrightarrow{\perp} ((3, 0), (3, 0))$,
 $(2, 0) \xrightarrow{\top} ((3, 1), (3, 0))$,
 $(2, 2) \xrightarrow{\perp} ((3, 1), (3, 0))$,
 $(2, 0) \xrightarrow{\perp} ((3, 0), \top)$]

Priority Queue: $Q_{app:2}$:

[

]

Output:
 $(2, 2) \xrightarrow{\top} \perp$



(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\min((3, 1), (2, 1))$

Priority Queue: $Q_{app:1}$:

[

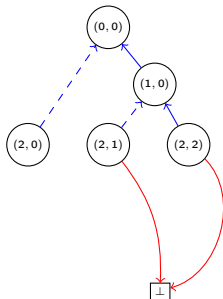
$(2, 1) \xrightarrow{\perp} ((3, 0), (3, 0))$,
 $(2, 0) \xrightarrow{\top} ((3, 1), (3, 0))$,
 $(2, 2) \xrightarrow{\perp} ((3, 1), (3, 0))$,
 $(2, 0) \xrightarrow{\perp} ((3, 0), \top)$]

Priority Queue: $Q_{app:2}$:

[

]

Output:
 $(1, 0) \xrightarrow{\top} (2, 2)$



(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\min((3, 0), (3, 0))$

Priority Queue: $Q_{app:1}$:

[

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

Priority Queue: $Q_{app:2}$:

[

]

Output:



(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\min((3, 0), (3, 0))$

Priority Queue: $Q_{app:1}$:

[

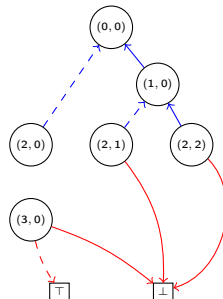
$(2, 1) \xrightarrow{\perp} ((3, 0), (3, 0))$,
 $(2, 0) \xrightarrow{\top} ((3, 1), (3, 0))$,
 $(2, 2) \xrightarrow{\perp} ((3, 1), (3, 0))$,
 $(2, 0) \xrightarrow{\perp} ((3, 0), \top)$]

Priority Queue: $Q_{app:2}$:

[

]

Output:
 $(3, 0) \xrightarrow{\perp} \top, (3, 0) \xrightarrow{\top} \perp$



(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\min((3, 0), (3, 0))$

Priority Queue: $Q_{app:1}$:

[

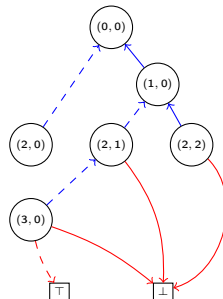
$(2, 0) \xrightarrow{\top} ((3, 1), (3, 0))$,
 $(2, 2) \xrightarrow{\perp} ((3, 1), (3, 0))$,
 $(2, 0) \xrightarrow{\perp} ((3, 0), \top)$]

Priority Queue: $Q_{app:2}$:

[

]

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



(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\min((3, 1), (3, 0))$

Priority Queue: $Q_{app:1}$:

[

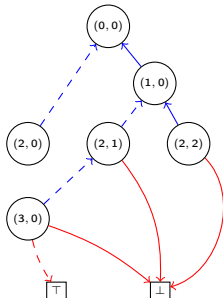
$(2, 0) \xrightarrow{\top} ((3, 1), (3, 0))$,
 $(2, 2) \xrightarrow{\perp} ((3, 1), (3, 0))$,
 $(2, 0) \xrightarrow{\perp} ((3, 0), \top)$]

Priority Queue: $Q_{app:2}$:

[

]

Output:



(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\min((3, 1), (3, 0))$

Priority Queue: $Q_{app:1}$:

[

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

Priority Queue: $Q_{app:2}$:

[

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

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

,

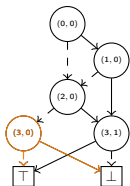
]

Output:



(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\min((3, 0), \top)$

Priority Queue: $Q_{app:1}$:

[

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

Priority Queue: $Q_{app:2}$:

[

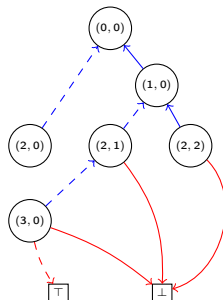
$(2, 0) \xrightarrow{\top} ((3, 1), (3, 0)) \quad (\top, \perp)$

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

,

]

Output:



(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\min((3, 0), \top)$

Priority Queue: $Q_{app:1}$:

[

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

Priority Queue: $Q_{app:2}$:

[

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

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

,

]

Output:
 $(3, 1) \xrightarrow{\perp} \top, (3, 1) \xrightarrow{\top} \perp$



(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\min((3, 0), \top)$

Priority Queue: $Q_{app:1}$:

[

]

Priority Queue: $Q_{app:2}$:

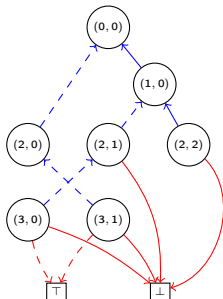
[

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

,

]

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



(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\max((3, 1), (3, 0))$

Priority Queue: $Q_{app:1}$:

[

]

Priority Queue: $Q_{app:2}$:

[

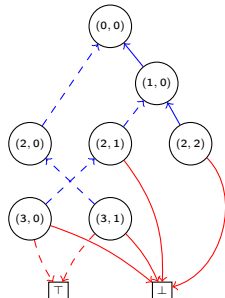
$(2, 0) \xrightarrow{\top} ((3, 1), (3, 0)) \quad (\top, \perp)$

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

,

]

Output:



(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\max((3, 1), (3, 0))$

Priority Queue: $Q_{app:1}$:

[

]

Priority Queue: $Q_{app:2}$:

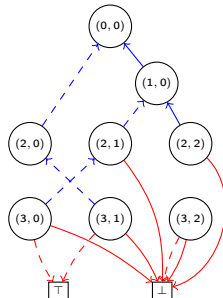
[

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

,

]

Output:
 $(3, 2) \xrightarrow{\perp} \perp, (3, 2) \xrightarrow{\top} \perp$



(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Seek:
 $\max((3, 1), (3, 0))$

Priority Queue: $Q_{app:1}$:

[

]

Priority Queue: $Q_{app:2}$:

[

]

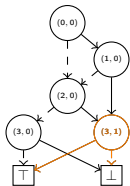
Output:

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



(c) $(a) \wedge (b)$

Apply : Example



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



(b) $\neg(x_0 ? x_2 \vee x_3 : x_2 \wedge x_3)$

Priority Queue: $Q_{app:1}$:

[

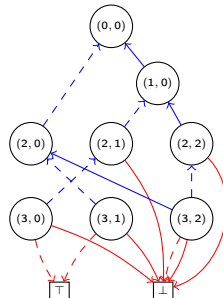
Priority Queue: $Q_{app:2}$:

[

]

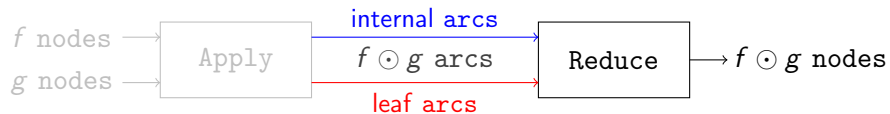
]

Output:



(c) $(a) \wedge (b)$

Apply



Apply (Reduce)



Time-Forward Processing

Send reduction t' with $Q_{red} : \text{PriorityQueue}\langle (s \rightarrow t') \rangle$ descending on parent s .

Apply (Reduce)



Time-Forward Processing

Send reduction t' with $Q_{red} : \text{PriorityQueue}\langle (s \rightarrow t') \rangle$ descending on parent s .

Apply (Reduce)



Time-Forward Processing

Send reduction t' with $Q_{red} : \text{PriorityQueue}\langle (s \rightarrow t') \rangle$ descending on parent s .

Observation (semi-transposition)

$\leftarrow : s \rightarrow t$ (Internal Arcs) provide parents of unreduced node t .

Apply (Reduce)



Time-Forward Processing

Send reduction t' with $Q_{red} : \text{PriorityQueue}\langle(s \rightarrow t')\rangle$ descending on parent s .

Observation (semi-transposition)

$\leftarrow : s \rightarrow t$ (Internal Arcs) provide parents of unreduced node t .

$\rightarrow : s \rightarrow \mathbb{B}$ (Terminal Arcs) are reduced and already sorted as per Q_{red} .

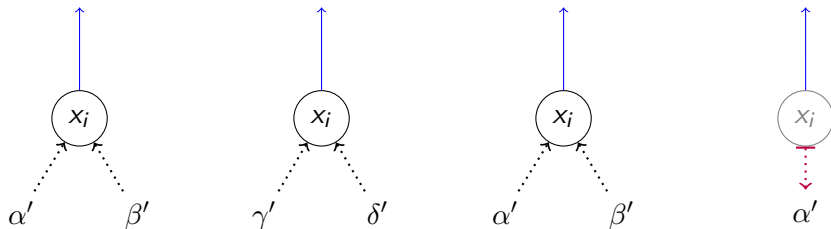
Apply (Reduce)



Reduce Level i :

- 1 Obtain nodes from Q_{red} and **terminal arcs**. Filter and **remember** redundant nodes.

Apply (Reduce)



Reduce Level i :

- 1 Obtain nodes from Q_{red} and **terminal arcs**. Filter and **remember** redundant nodes.

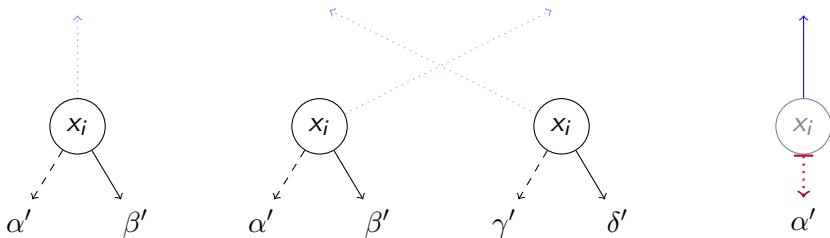
Apply (Reduce)



Reduce Level i :

- 1 Obtain nodes from Q_{red} and **terminal arcs**. Filter and **remember** redundant nodes.

Apply (Reduce)



Reduce Level i :

- 1 Obtain nodes from Q_{red} and **terminal arcs**. Filter and **remember** redundant nodes.
- 2 Sort remaining nodes by children, output unique nodes, and **remember** duplications.

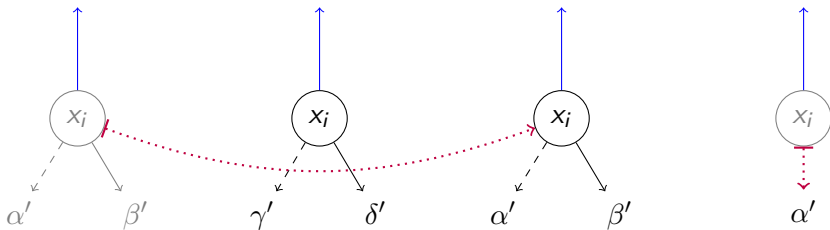
Apply (Reduce)



Reduce Level i :

- 1 Obtain nodes from Q_{red} and **terminal arcs**. Filter and **remember** redundant nodes.
- 2 Sort remaining nodes by children, output unique nodes, and **remember** duplications.

Apply (Reduce)



Reduce Level i :

- 1 Obtain nodes from Q_{red} and **terminal arcs**. Filter and **remember** redundant nodes.
- 2 Sort remaining nodes by children, output unique nodes, and **remember** duplications.
- 3 Sort back to match **internal arcs** and forward to parents with Q_{red} .

Apply (Reduce)



Reduce Level i :

- 1 Obtain nodes from Q_{red} and **terminal arcs**. Filter and **remember** redundant nodes.
- 2 Sort remaining nodes by children, output unique nodes, and **remember** duplications.
- 3 Sort back to match **internal arcs** and forward to parents with Q_{red} .

Apply (Reduce) : *Example*



(c) $(a) \wedge (b)$

(d) $(a) \wedge (b)$ reduced

Apply (Reduce) : *Example*



(c) $(a) \wedge (b)$

Level: 3

[$[(3, 2) \mapsto \perp]$]

(d) $(a) \wedge (b)$ reduced

Apply (Reduce) : *Example*



(c) $(a) \wedge (b)$

Level: 3
 $[\quad [(3, 2) \mapsto \perp] \quad]$
 $[\quad ((3, 1), \top, \perp) \quad , \quad]$

(d) $(a) \wedge (b)$ reduced

Apply (Reduce) : *Example*



(c) $(a) \wedge (b)$

Level: 3
 $[\quad [(3, 2) \mapsto \perp] \quad]$
 $[\quad ((3, 1), \top, \perp) \quad , \quad ((3, 0), \top, \perp) \quad]$

(d) $(a) \wedge (b)$ reduced

Apply (Reduce) : *Example*



(c) $(a) \wedge (b)$

Level: 3
 $[\quad [(3, 2) \mapsto \perp] \quad]$
 $[\quad [(3, 1) \mapsto (3, \max)] \quad , \quad]$
 $\quad \quad \quad ((3, 0), \top, \perp)$

Output:
 $((3, \max), \top, \perp)$



(d) $(a) \wedge (b)$ reduced

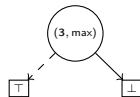
Apply (Reduce) : *Example*



(c) $(a) \wedge (b)$

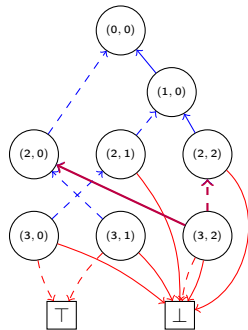
Level: 3
 $\left[\begin{array}{c} [(3, 2) \mapsto \perp] \\ [(3, 1) \mapsto (3, \max)] \\ [(3, 0) \mapsto (3, \max)] \end{array} \right]$

Output:



(d) $(a) \wedge (b)$ reduced

Apply (Reduce) : *Example*



(c) $(a) \wedge (b)$

Priority Queue: Q_{red} :

[$(2, 2) \xrightarrow{\perp} \perp$,

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

]

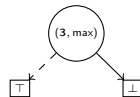
Level: 3

[

[$(3, 1) \mapsto (3, \max)$] ,

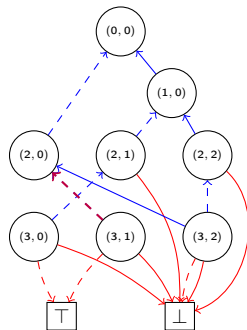
[$(3, 0) \mapsto (3, \max)$]]

Output:



(d) $(a) \wedge (b)$ reduced

Apply (Reduce) : *Example*



(c) $(a) \wedge (b)$

Priority Queue: Q_{red} :

[$(2, 2) \xrightarrow{\perp} \perp$,

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

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

]

Level: 3

[

]

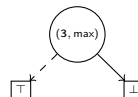
[

$[(3, 0) \mapsto (3, \max)]$

,

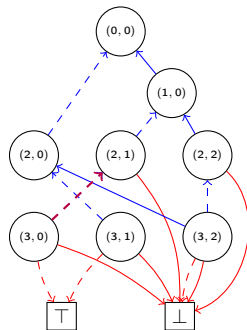
]

Output:



(d) $(a) \wedge (b)$ reduced

Apply (Reduce) : *Example*



(c) $(a) \wedge (b)$

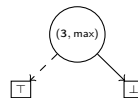
Priority Queue: Q_{red} :

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

Level: 3

[
 [
 ,
]
]

Output:



(d) $(a) \wedge (b)$ reduced

Apply (Reduce) : *Example*



(c) $(a) \wedge (b)$

Priority Queue: Q_{red} :

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

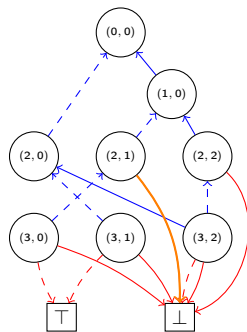
[
 Level: 2
 $[(2, 2) \mapsto \perp]$
]

Output:



(d) $(a) \wedge (b)$ reduced

Apply (Reduce) : *Example*



(c) $(a) \wedge (b)$

Priority Queue: Q_{red} :

[

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

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

]

Level: 2

[

$[(2, 2) \mapsto \perp]$

]

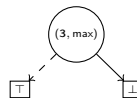
[

$((2, 1), (3, \max), \perp)$

,

]

Output:



(d) $(a) \wedge (b)$ reduced

Apply (Reduce) : *Example*



(c) $(a) \wedge (b)$

Priority Queue: Q_{red} :

[

]

Level: 2

[

$[(2, 2) \mapsto \perp]$

]

[

$((2, 1), (3, \max), \perp)$

,

$((2, 0), (3, \max), \perp)$

]

Output:



(d) $(a) \wedge (b)$ reduced

Apply (Reduce) : Example



(c) $(a) \wedge (b)$

Priority Queue: Q_{red} :

[

]

Level: 2

[

$[(2, 2) \mapsto \perp]$

]

[

$[(2, 1) \mapsto (2, \max)]$

,

$((2, 0), (3, \max), \perp)$

]

Output:
 $((2, \max), (3, \max), \perp)$



(d) $(a) \wedge (b)$ reduced

Apply (Reduce) : *Example*



(c) $(a) \wedge (b)$

Priority Queue: Q_{red} :

[

]

Level: 2

[

$[(2, 2) \mapsto \perp]$

]

[

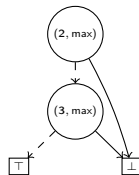
$[(2, 1) \mapsto (2, \max)]$

,

$[(2, 0) \mapsto (2, \max)]$

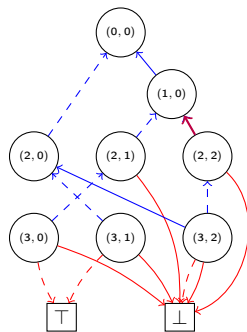
]

Output:



(d) $(a) \wedge (b)$ reduced

Apply (Reduce) : *Example*



(c) $(a) \wedge (b)$

Priority Queue: Q_{red} :

[

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

]

Level: 2

[

]

[

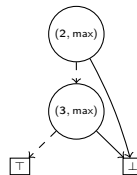
$[(2, 1) \mapsto (2, \max)]$

,

$[(2, 0) \mapsto (2, \max)]$

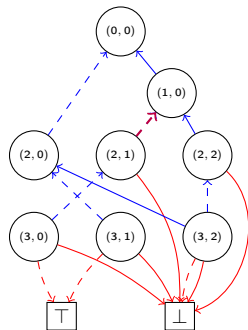
]

Output:



(d) $(a) \wedge (b)$ reduced

Apply (Reduce) : *Example*



(c) $(a) \wedge (b)$

Priority Queue: Q_{red} :

[

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

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

]

Level: 2

[

[

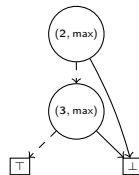
$[(2, 0) \mapsto (2, \max)]$

]

,

]

Output:



(d) $(a) \wedge (b)$ reduced

Apply (Reduce) : Example



(c) $(a) \wedge (b)$

Priority Queue: Q_{red} :

[

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

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

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

Level: 2

[

[

]

,
]

Output:



(d) $(a) \wedge (b)$ reduced

Apply (Reduce) : *Example*



(c) $(a) \wedge (b)$

Priority Queue: Q_{red} :

[

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

Level: 1

[

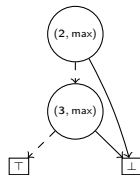
]

[

$((1, 0), (2, \max), \perp)$

]

Output:



(d) $(a) \wedge (b)$ reduced

Apply (Reduce) : Example



(c) $(a) \wedge (b)$

Priority Queue: Q_{red} :

[

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

Level: 1

[

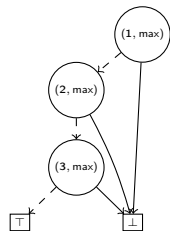
]

[

$[(1,0) \mapsto (1, \max)]$

]

Output:
 $((1, \max), (2, \max), \perp)$



(d) $(a) \wedge (b)$ reduced

Apply (Reduce) : *Example*



(c) $(a) \wedge (b)$

Priority Queue: Q_{red} :

[

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

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

Level: 1

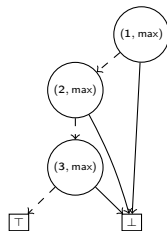
[

]

[

]

Output:



(d) $(a) \wedge (b)$ reduced

Apply (Reduce) : *Example*



(c) $(a) \wedge (b)$

Priority Queue: Q_{red} :

[

]

Level: 0

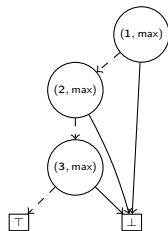
[

]

[$((0,0), (2, \max), (1, \max))$]

]

Output:



(d) $(a) \wedge (b)$ reduced

Apply (Reduce) : Example



(c) $(a) \wedge (b)$

Priority Queue: Q_{red} :

[

]

Level: 0

[

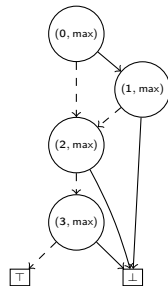
]

$[(0, 0) \mapsto (0, \max)]$

[

]

Output:
 $((0, \max), (2, \max), (1, \max))$



(d) $(a) \wedge (b)$ reduced

Apply (Reduce) : *Example*



(c) $(a) \wedge (b)$

Priority Queue: Q_{red} :

[

]

Level: 0

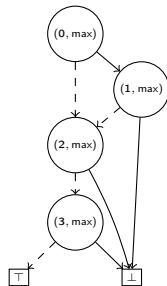
[

]

[

]

Output:



(d) $(a) \wedge (b)$ reduced

Algorithm	I/O-Complexity
bdd_pathcount	$O(\text{sort}(N_f))$
bdd_not	$2N_f/B$
bdd_restrict	$O(\text{sort}(N_f))$
bdd_apply	$O(\text{sort}(N_f \cdot N_g))$



—○— Adiar —○— BuDDy —◆— CUDD —□— Sylvan

Running time for the *N-Queens* problems.



Running time for the *N-Queens* problems.

Contents

What are Binary Decision Diagrams?

Why do they break?

How can we fix it?

CountPaths

Apply

Equality Checking

Algorithm	I/O-Complexity
bdd_pathcount	$O(\text{sort}(N_f))$
bdd_not	$2N_f/B$
bdd_restrict	$O(\text{sort}(N_f))$
bdd_apply	$O(\text{sort}(N_f \cdot N_g))$

Algorithm	I/O-Complexity
bdd_pathcount	$O(\text{sort}(N_f))$
bdd_not	$2N_f/B$
bdd_restrict	$O(\text{sort}(N_f))$
bdd_apply	$O(\text{sort}(N_f \cdot N_g))$
bdd_equal	?

Equality Checking

$$f \leftrightarrow g \equiv \top$$

Equality Checking

$$f \leftrightarrow g \equiv \top$$

$$\underbrace{O(\text{sort}(N^2))}_{\text{Apply}} + \underbrace{O(\text{sort}(N^2))}_{\text{Reduce}} + \underbrace{O(1)}_{\text{check is } \top} = O(\text{sort}(N^2))$$

Equality Checking

Theorem (Bryant '86)

Let π be a variable order and $f : \mathbb{B}^n \rightarrow \mathbb{B}$ then there exists a unique (up to isomorphism) Reduced Ordered Binary Decision Diagram representing f with ordering π .

Equality Checking

Theorem (Bryant '86)

Let π be a variable order and $f : \mathbb{B}^n \rightarrow \mathbb{B}$ then there exists a unique (up to isomorphism) Reduced Ordered Binary Decision Diagram representing f with ordering π .

Trivial cases: $f \neq g$ if there is a mismatch in

- $N_f \neq N_g$ Number of nodes $O(1)$ I/Os
- $L_f \neq L_g$ Number of levels $O(1)$ I/Os
- $N_{f,i} \neq N_{g,i}$ Number of nodes on a level $O(L/B)$ I/Os
- $L_{f,i} \neq L_{g,i}$ Label of an i th level $O(L/B)$ I/Os

Equality Checking

Theorem (Bryant '86)

Let π be a variable order and $f : \mathbb{B}^n \rightarrow \mathbb{B}$ then there exists a unique (up to isomorphism) Reduced Ordered Binary Decision Diagram representing f with ordering π .



Equality Checking

Theorem (Bryant '86)

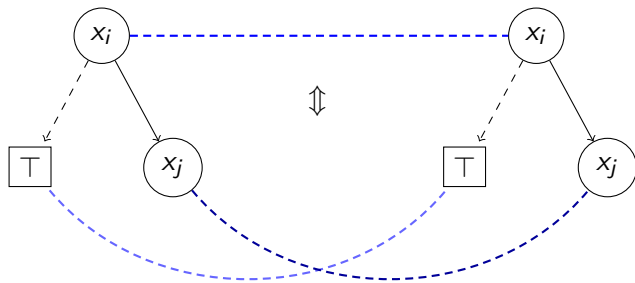
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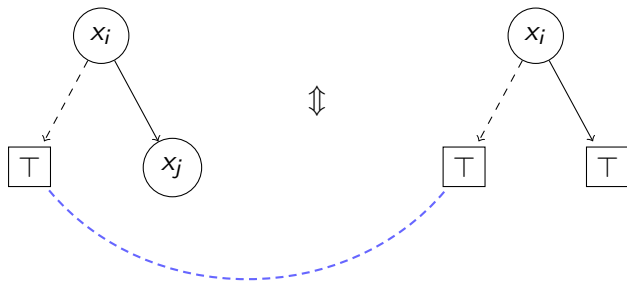
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Theorem (Bryant '86)

Let π be a variable order and $f : \mathbb{B}^n \rightarrow \mathbb{B}$ then there exists a unique (up to isomorphism) Reduced Ordered Binary Decision Diagram representing f with ordering π .

`IsIsomorphic(f , g)`

- Check whether root v_f of f and root v_g of g have a local violation.
- Check $low(v_f) \sim low(v_g)$ and $high(v_f) \sim high(v_g)$ “recursively”.

Return false on first violation. If there are no violations then return true.

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$\text{IsIsomorphic}(f, g)$

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- Check $\text{low}(v_f) \sim \text{low}(v_g)$ and $\text{high}(v_f) \sim \text{high}(v_g)$ “recursively”.

Return false on first violation. If there are no violations then return true.

$$\underbrace{O(\text{sort}(N^2))}_{\text{Apply'}} + \underbrace{\cancel{O(\text{sort}(N^2))}}_{\text{Reduce}} + \underbrace{\cancel{O(1)}}_{\text{check is } \top} = O(\text{sort}(N^2))$$

Equality Checking

Theorem (Bryant '86)

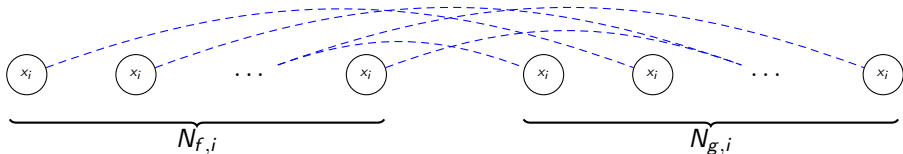
Let π be a variable order and $f : \mathbb{B}^n \rightarrow \mathbb{B}$ then there exists a unique (up to isomorphism) Reduced Ordered Binary Decision Diagram representing f with ordering π .



Equality Checking

Theorem (Bryant '86)

Let π be a variable order and $f : \mathbb{B}^n \rightarrow \mathbb{B}$ then there exists a unique (up to isomorphism) Reduced Ordered Binary Decision Diagram representing f with ordering π .



Return false if more than $N_{f,i} = N_{g,i}$ pairs of nodes are checked on level i .

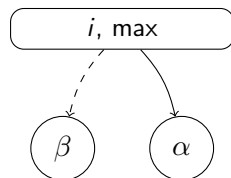
$$\underbrace{O(\text{sort}(\sum_i N_{f,i}))}_{\text{Apply}''} = O(\text{sort}(N))$$

Equality Checking

Observation

Each level output by the Reduce algorithm has the following properties:

Equality Checking



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Observation

Each level output by the Reduce algorithm has the following properties:

- Nodes on level i have their identifiers *consecutively* numbered.

Equality Checking



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- Nodes on level i have their identifiers *consecutively* numbered.

Equality Checking



Observation

Each level output by the Reduce algorithm has the following properties:

- Nodes on level i have their identifiers *consecutively* numbered.
- Nodes on level i are output sorted by their children.

Equality Checking

Theorem

If G_f and G_g are outputs of Reduce.

$G_f \sim G_g \iff \text{For all } i \in [0; N_f) \text{ the node } G_f[i] \text{ matches } G_g[i] \text{ numerically.}$

Proof.

\Leftarrow : Must describe the exact same graph.

\Rightarrow : Strong induction on BDD levels bottom-up.



Equality Checking

Theorem

If G_f and G_g are outputs of Reduce.

$G_f \sim G_g \iff \text{For all } i \in [0; N_f) \text{ the node } G_f[i] \text{ matches } G_g[i] \text{ numerically.}$

Proof.

\Leftarrow : Must describe the exact same graph.

\Rightarrow : Strong induction on BDD levels bottom-up. □

Corollary

If G_f and G_g are outputs of Reduce then $f \equiv g$ is computable using $2 \cdot N/B$ I/Os.

Equality Checking

Algorithm	Time (s)
$f \leftrightarrow g \equiv \top$	0.38

Checking the (EPFL Benchmark) *voter* circuit's single output gate ($|N_f| = |N_g| = 5.76$ MiB).

Equality Checking

Algorithm	Time (s)
$f \leftrightarrow g \equiv \top$	0.38
$O(\text{sort}(N))$	0.058

Checking the (EPFL Benchmark) *voter* circuit's single output gate ($|N_f| = |N_g| = 5.76$ MiB).

Equality Checking

Algorithm	Time (s)
$f \leftrightarrow g \equiv \top$	0.38
$O(\text{sort}(N))$	0.058
$2N/B$	0.006

Checking the (EPFL Benchmark) *voter* circuit's single output gate ($|N_f| = |N_g| = 5.76$ MiB).

Steffan Christ Sølvsten

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🐦 [@ssoelvsten](https://twitter.com/ssoelvsten)

Adiar

📄 github.com/ssoelvsten/adiar

📖 ssoelvsten.github.io/adiar



Algorithm	Depth-First	Time-Forwarded
bdd_pathcount	$O(N_f)$	$O(\text{sort}(N_f))$
bdd_not	$O(N_f)$	$2N_f/B$
bdd_restrict	$O(N_f)$	$O(\text{sort}(N_f))$
bdd_apply	$O(N_f N_g)$	$O(\text{sort}(N_f N_g))$
bdd_equal	$O(1)$	$2N/B$