WELCOME TO TUTORIAL

Session 5.1 Janus-SAT: A Hybrid Quantum-Classical Solver for 3-SAT Problems

ACES Lab
ADVANCED COMPUTING AND EMERGING SERVICE LAB

JanusQ Cloud

浙江大学 计算机科学与技术学院
COLLEGE OF COMPUTER SCIENCE AND TECHNOLOGY
ZHEJIANG UNIVERSITY

https://janusq.github.io/tutorials/

College of Computer Science and Technology,
Zhejiang University

ASPLOS 2024

Outline of Presentation

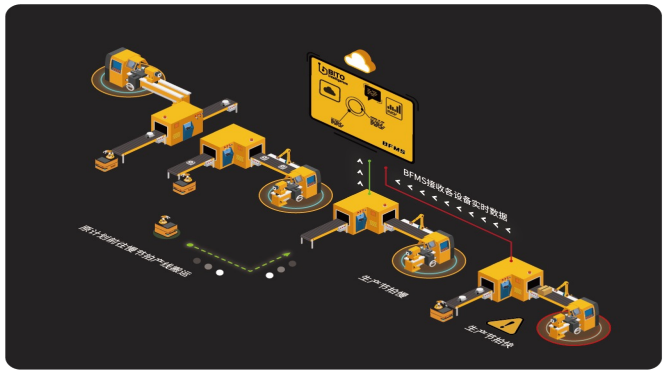
- **Background and challenges**
- HyQSAT overview
- Frontend
- Backend
- Experiment
- API of HyQSAT

Applications of SAT Problem

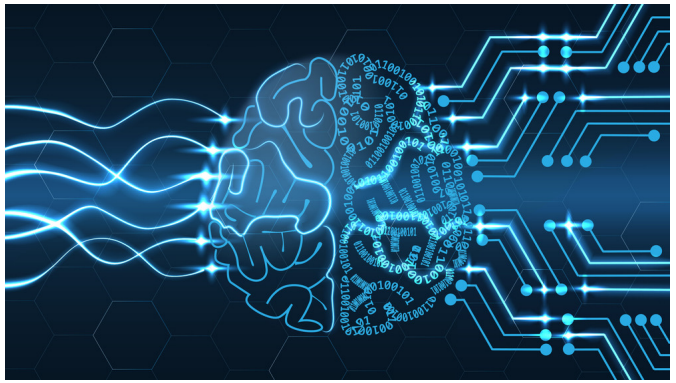
Propositional satisfiability problem (SAT)

Cryptography

Software Testing



Planning



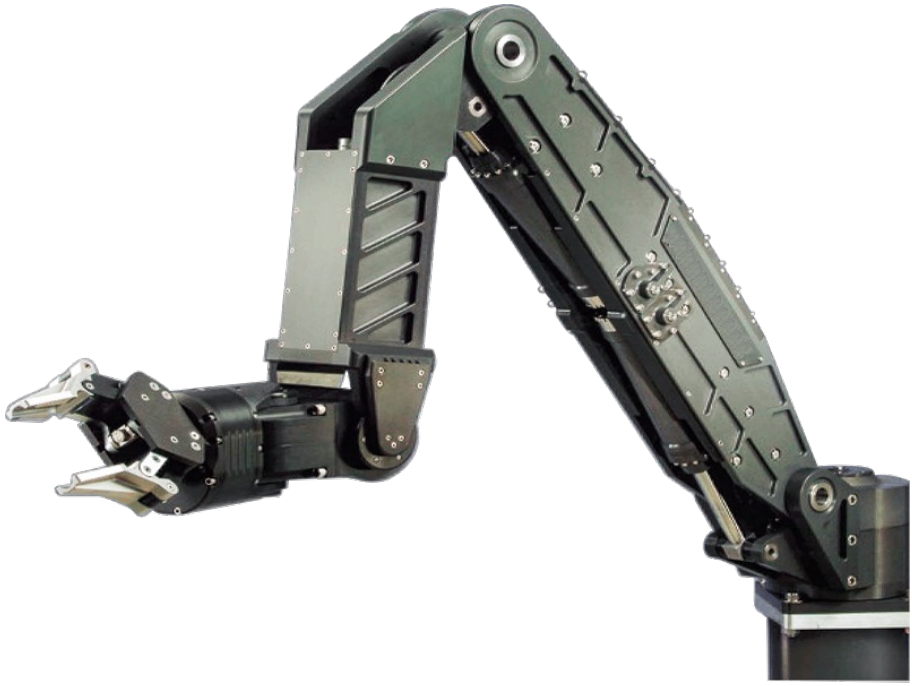
Artificial Intelligence

Protein structure analysis
Knowledge inference ……

Example: A Motor Vehicle Parts Production Line

A product line can produce **1,000** products per day.

20,000 products need to be produced, including **A, B, C, D….**



Constraints:

A and B must be produced together;

B must be produced together with one of E, F or G;

C cannot be produced with E together ;

……

The optimal classical algorithm takes 3 days to find the optimal schedule.

Formulation the SAT Problem: An Example

A SAT problem **C** in a **conjunctive normal form** with variables x_1 , x_2, x_2, x_4 :

$$C = c_1 \wedge c_2$$

$$c_1 = x_1 \vee x_2 \vee x_3$$

$$c_1 = \neg x_1 \vee x_2 \vee x_3$$

The **clause** means : x_1 or x_2 or x_2

A **solution** of the given problem:

$$x_1 = x_2 = 0$$
$$x_3 = x_4 = 1$$

All clauses need to be satisfied.

3-SAT problem: each clause has no more then 3 variables. **The first NP-complete problem.**

Optimal Classical Algorithm: CDCL Algorithm

Tree search

$c_1 = x_1 \vee x_2 \vee x_3$
$c_2 = x_2 \vee \neg x_3 \vee x_4$
$c_3 = x_2 \vee \neg x_4$

Input problem

Optimal Classical Algorithm: CDCL Algorithm

Apply a tree search strategy with tree steps:

1) Decision
2) Propagation
3) Conflict resolving

$c_1 = x_1 \vee x_2 \vee x_3$
$c_2 = x_2 \vee \neg x_3 \vee x_4$
$c_3 = x_2 \vee \neg x_4$

Input problem

$x_1 = 0$

1) Decision

Optimal Classical Algorithm: CDCL Algorithm

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Input problem

$x_1 = 0$

1) Decision

$$c_1 = x_2 \vee x_3$$
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Optimal Classical Algorithm: CDCL Algorithm

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Input problem

↓

$x_1 = 0$

1) Decision

↓

$$c_1 = x_2 \vee x_3$$
$$c_2 = x_2 \vee \neg x_3 \vee x_4$$
$$c_3 = x_2 \vee \neg x_4$$

↓

$x_2 = 0$

1) Decision

↓

$$c_1 = x_3$$
$$c_2 = \neg x_3 \vee x_4$$
$$c_3 = \neg x_4$$

Optimal Classical Algorithm: CDCL Algorithm

Apply a tree search strategy with tree steps:

1) Decision
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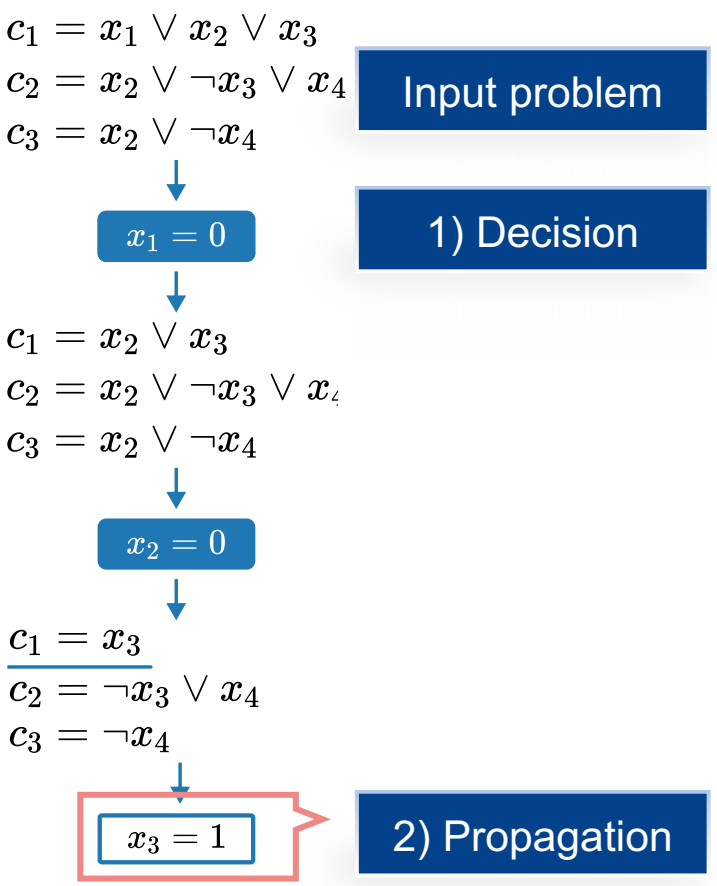

Optimal Classical Algorithm: CDCL Algorithm

Apply a tree search strategy with tree steps:

1) Decision
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$$c_1 = x_1 \vee x_2 \vee x_3$$
$$c_2 = x_2 \vee \neg x_3 \vee x_4$$
$$c_3 = x_2 \vee \neg x_4$$

Input problem

$$\downarrow$$

$$x_1 = 0$$

1) Decision

$$\downarrow$$

$$c_1 = x_2 \vee x_3$$
$$c_2 = x_2 \vee \neg x_3 \vee x_4$$
$$c_3 = x_2 \vee \neg x_4$$

$$\downarrow$$

$$x_2 = 0$$

$$\downarrow$$

$$\underline{c_1 = x_3}$$
$$c_2 = \neg x_3 \vee x_4$$
$$c_3 = \neg x_4$$

$$\downarrow$$

$$\boxed{x_3 = 1}$$

2) Propagation

$$\downarrow$$

$$\underline{c_2 = x_4}$$
$$c_3 = \neg x_4$$

Optimal Classical Algorithm: CDCL Algorithm

Apply a tree search strategy with tree steps:

1) Decision
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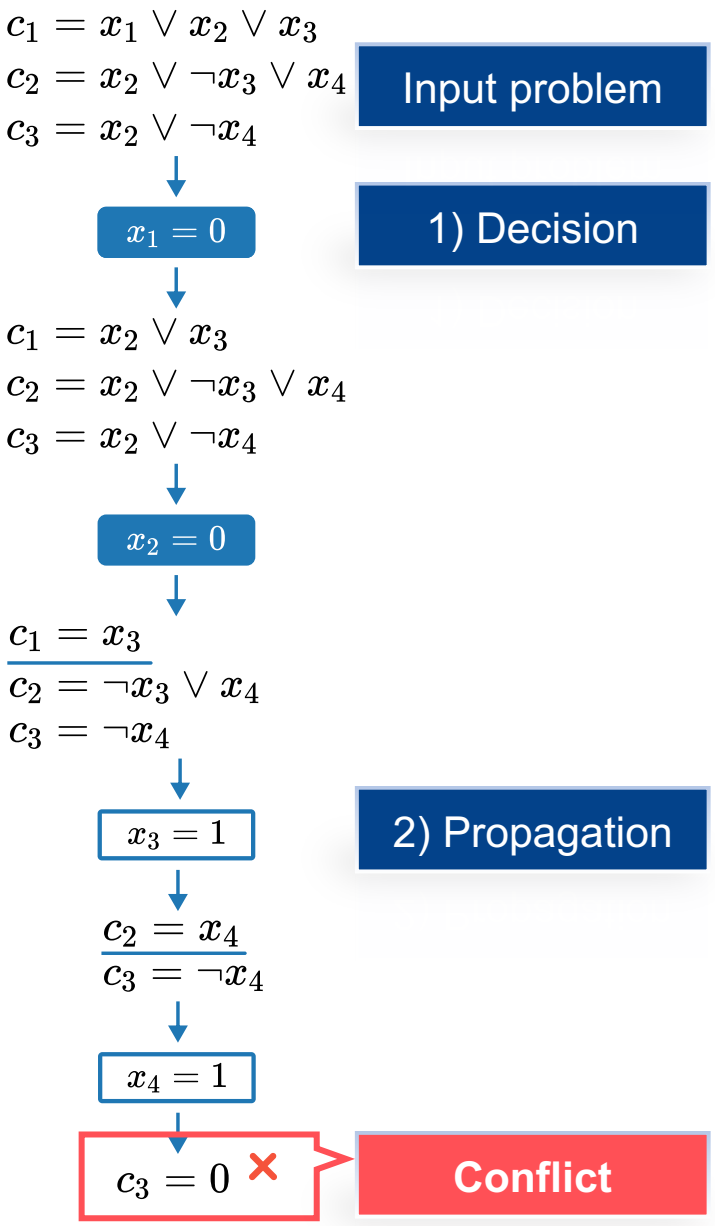
3) Conflict resolving



Optimal Classical Algorithm: CDCL Algorithm

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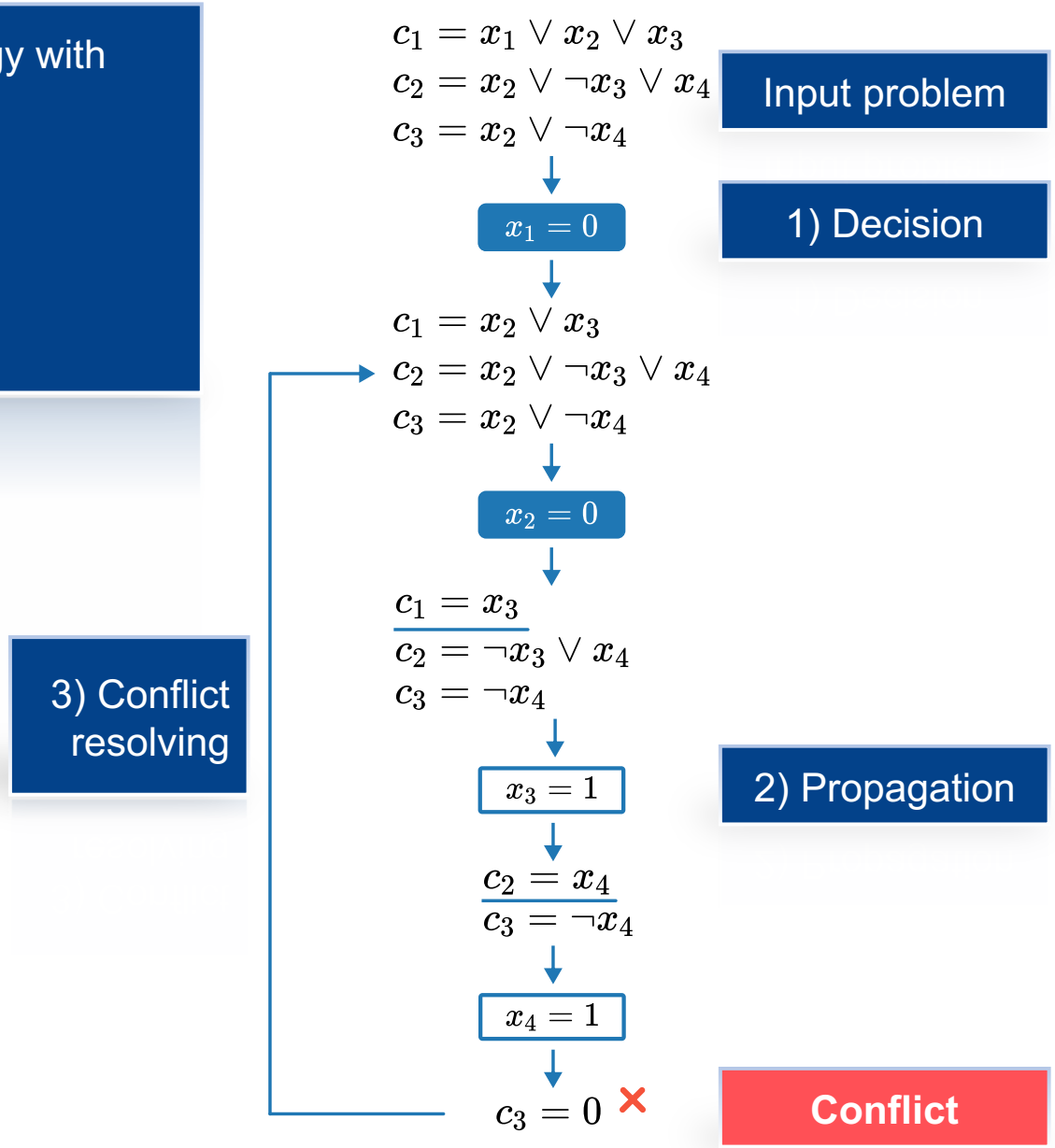

Optimal Classical Algorithm: CDCL Algorithm

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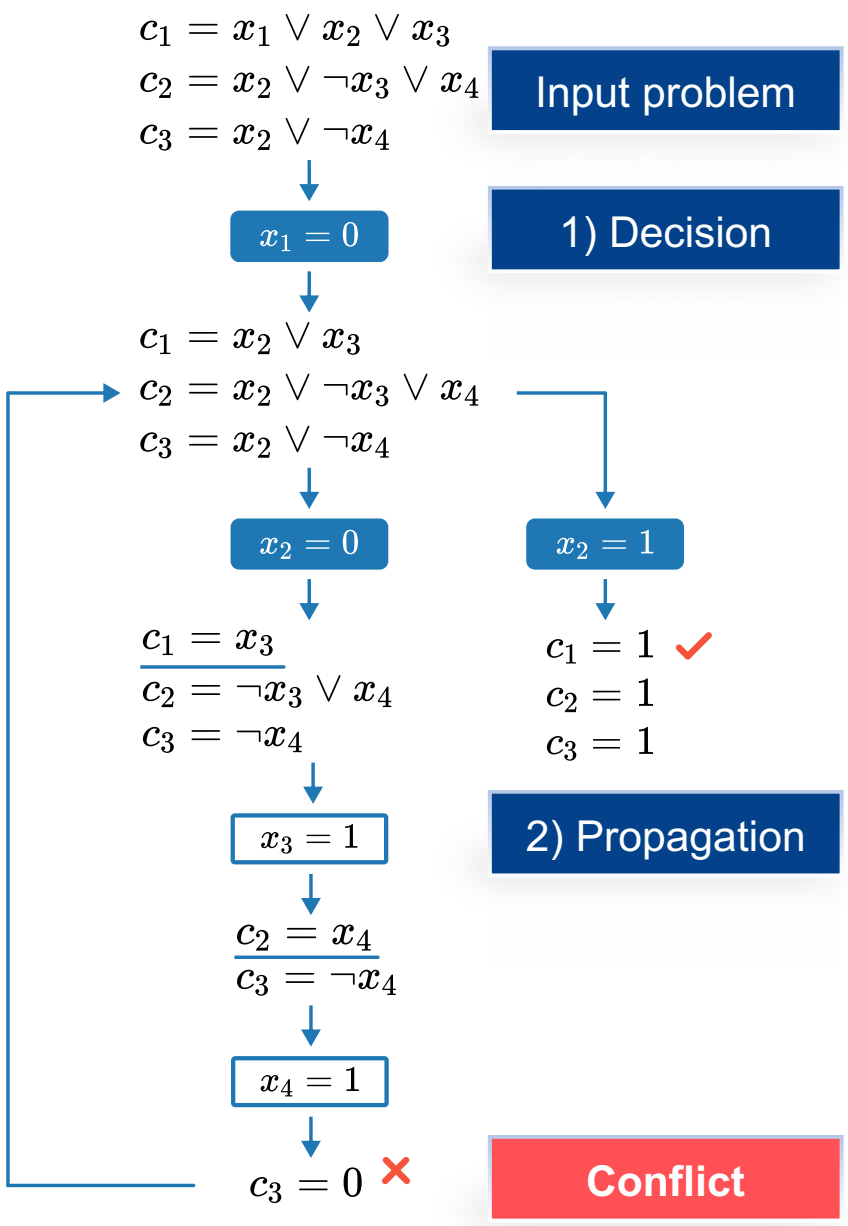
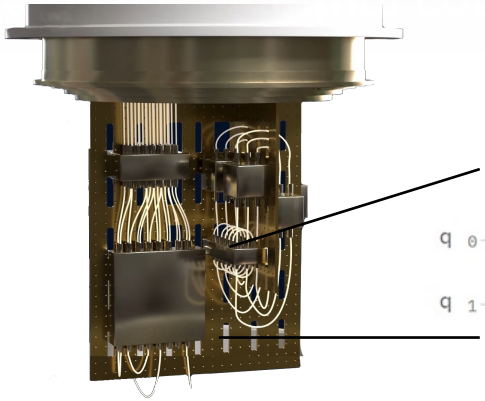
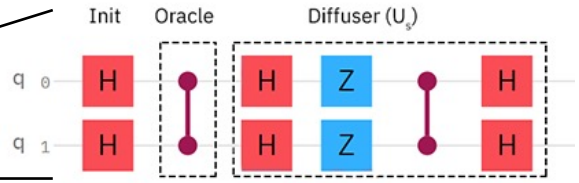


Solving 3-SAT Problems by Quantum Computing

Gate-based quantum computer

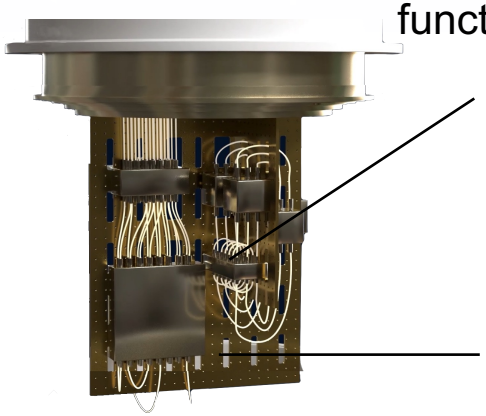


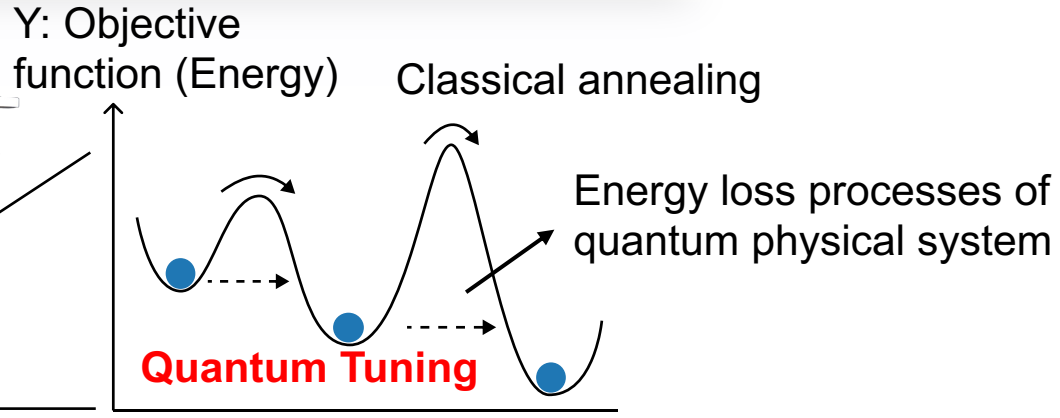
Grover Algorithm, VQE Algorithm



Quantum circuit

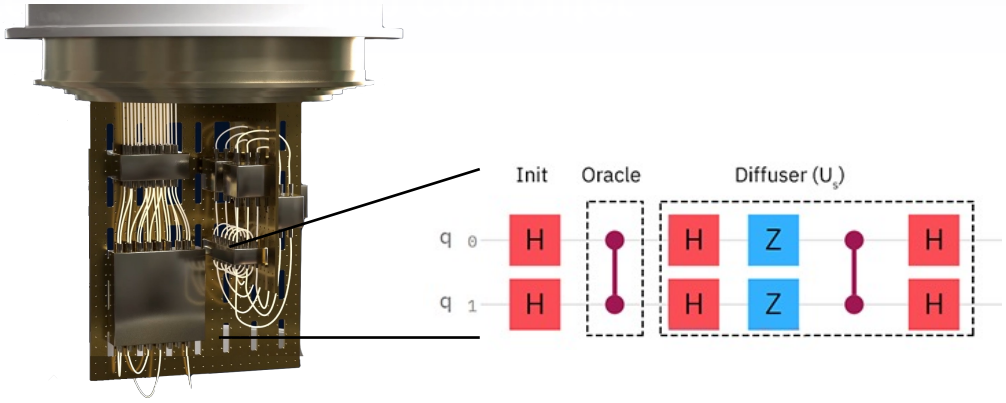
Quantum annealer



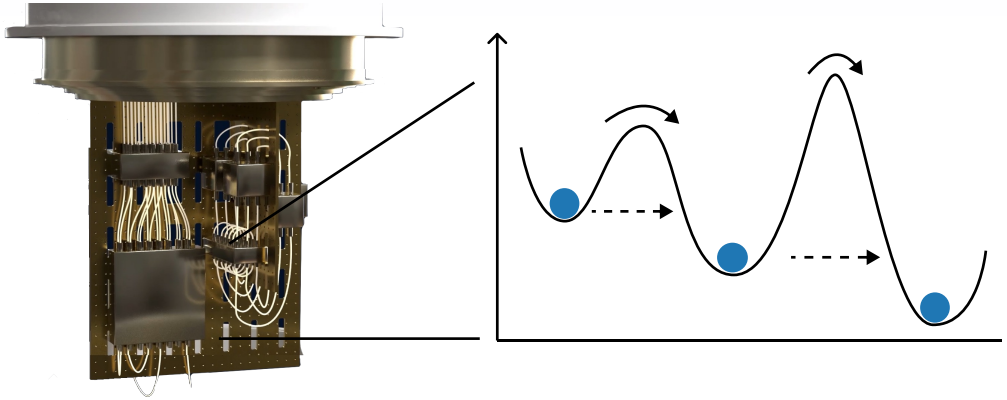


Solving 3-SAT Problems by Quantum Computing

Gate-based quantum computer



Quantum annealer



Quantum		Classical
Gate-based	**Quantum annealing (QA)**	**CDCL**
Digital	Simulated	Digital
Quantum superposition	Quantum tunneling	Classical physics
$O(\sqrt{L})$	$O(e^{\sqrt{L}})$	$O(e^{L})$
~100 qubits	~2000 qubits	>2^{30} bits
~10 variables	~50 variables	~1000 variables

Deploying 3-SAT Problem to Quantum Annealer

The 3-SAT problem first should be transferred into the **minimization problem of a quadratic polynomial objective function**, formulated as:

Configured

$$\arg\min_{X} \; H_C(X) = I + \sum_{i=1}^{L} B_i x_i + \sum_{i=1}^{L} \sum_{j=i+1}^{L} J_{i,j} x_i x_j,$$

Example:

$$C = c_1 \wedge c_2$$
$$c_1 = x_1 \vee x_2 \vee x_3,$$
$$c_2 = \neg x_2 \vee \neg x_3 \vee x_4$$

$$\begin{aligned} H_C(X, A) = 3 &+ x_1 + 3x_2 - 2x_3 \\ &- x_4 - 2a_2 + x_1 x_2 \\ &- x_2 x_3 - 2a_1 x_1 - 2a_1 x_2 \\ &+ a_1 x_3 - 2a_2 x_2 + 2a_2 x_3 \\ &+ a_2 x_4 \end{aligned}$$

Deploying 3-SAT Problem to Quantum Annealer

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Step 1

$$C = c_1 \wedge c_2$$
$$c_1 = x_1 \vee x_2 \vee x_3,$$
$$c_2 = \neg x_2 \vee \neg x_3 \vee x_4$$

3-SAT problem

Deploying 3-SAT Problem to Quantum Annealer

Step 1

$$C = c_1 \wedge c_2$$
$$c_1 = x_1 \vee x_2 \vee x_3,$$
$$c_2 = \neg x_2 \vee \neg x_3 \vee x_4$$

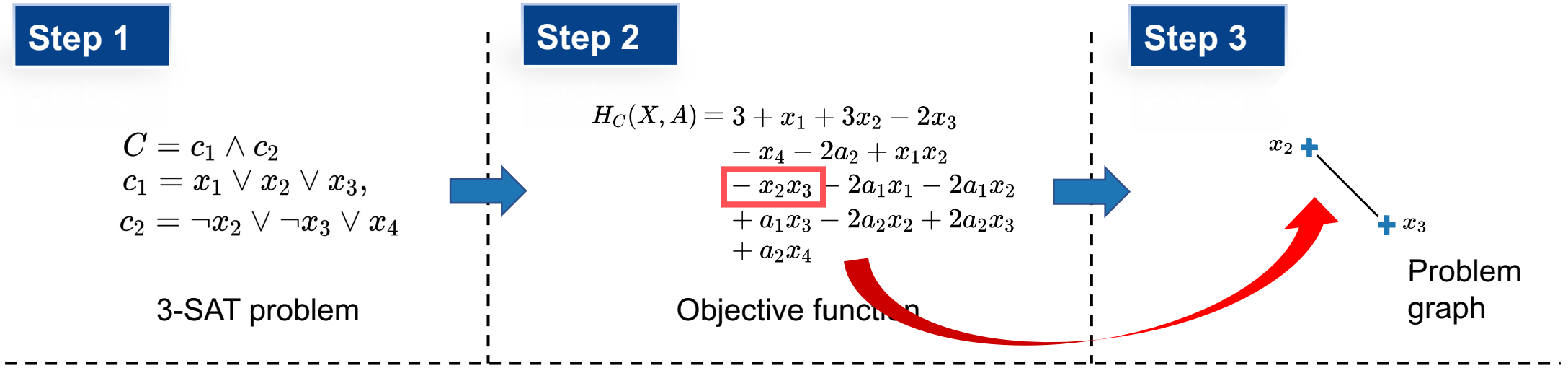
3-SAT problem

Step 2

$$\begin{aligned} H_C(X, A) = 3 &+ x_1 + 3x_2 - 2x_3 \\ &- x_4 - 2a_2 + x_1x_2 \\ &- x_2x_3 - 2a_1x_1 - 2a_1x_2 \\ &+ a_1x_3 - 2a_2x_2 + 2a_2x_3 \\ &+ a_2x_4 \end{aligned}$$

Objective function

Deploying 3-SAT Problem to Quantum Annealer



Deploying 3-SAT Problem to Quantum Annealer

Step 1

$$C = c_1 \wedge c_2$$
$$c_1 = x_1 \vee x_2 \vee x_3,$$
$$c_2 = \neg x_2 \vee \neg x_3 \vee x_4$$

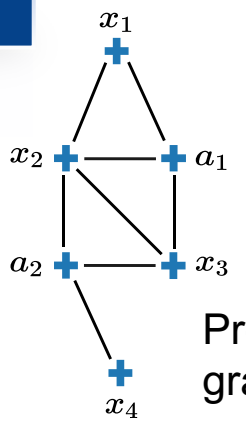
3-SAT problem

Step 2

$$H_C(X, A) = 3 + x_1 + 3x_2 - 2x_3 - x_4 - 2a_2 + x_1x_2 - x_2x_3 - 2a_1x_1 - 2a_1x_2 + a_1x_3 - 2a_2x_2 + 2a_2x_3 + a_2x_4$$

Objective function

Step 3



Problem graph

Deploying 3-SAT Problem to Quantum Annealer

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Step 1

$$C = c_1 \wedge c_2$$
$$c_1 = x_1 \vee x_2 \vee x_3,$$
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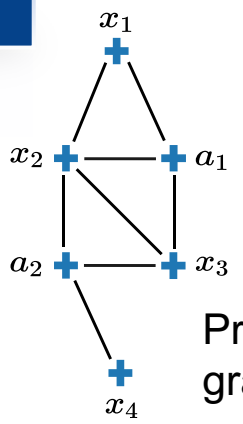
3-SAT problem

Step 2

$$\begin{aligned} H_C(X, A) = 3 &+ x_1 + 3x_2 - 2x_3 \\ &- x_4 - 2a_2 + x_1x_2 \\ &- x_2x_3 - 2a_1x_1 - 2a_1x_2 \\ &+ a_1x_3 - 2a_2x_2 + 2a_2x_3 \\ &+ a_2x_4 \end{aligned}$$

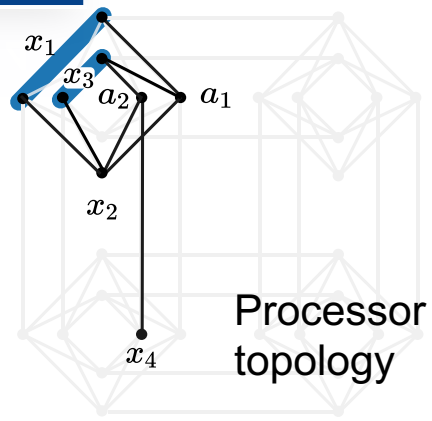
Objective function

Step 3



Problem graph

Step 4



Processor topology

Embedding

Deploying 3-SAT Problem to Quantum Annealer

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Step 1

$$C = c_1 \wedge c_2$$
$$c_1 = x_1 \vee x_2 \vee x_3,$$
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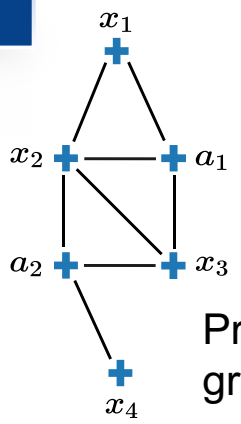
3-SAT problem

Step 2

$$H_C(X, A) = 3 + x_1 + 3x_2 - 2x_3 - x_4 - 2a_2 + x_1x_2 - x_2x_3 - 2a_1x_1 - 2a_1x_2 + a_1x_3 - 2a_2x_2 + 2a_2x_3 + a_2x_4$$

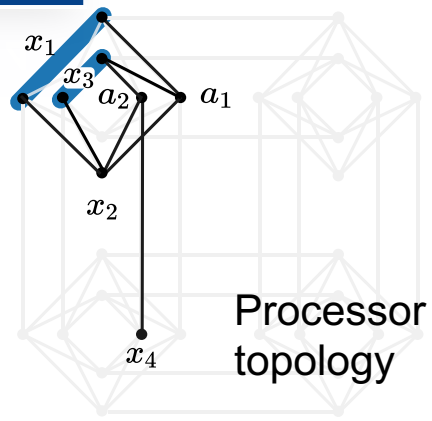
Objective function

Step 3



Problem graph

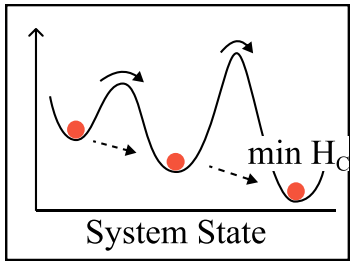
Step 4



Processor topology

Embedding

Step 5



Quantum Annealing

Deploying 3-SAT Problem to Quantum Annealer

Step 1

$$C = c_1 \wedge c_2$$
$$c_1 = x_1 \vee x_2 \vee x_3,$$
$$c_2 = \neg x_2 \vee \neg x_3 \vee x_4$$

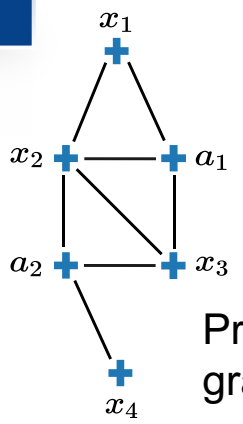
3-SAT problem

Step 2

$$H_C(X, A) = 3 + x_1 + 3x_2 - 2x_3 - x_4 - 2a_2 + x_1x_2 - x_2x_3 - 2a_1x_1 - 2a_1x_2 + a_1x_3 - 2a_2x_2 + 2a_2x_3 + a_2x_4$$

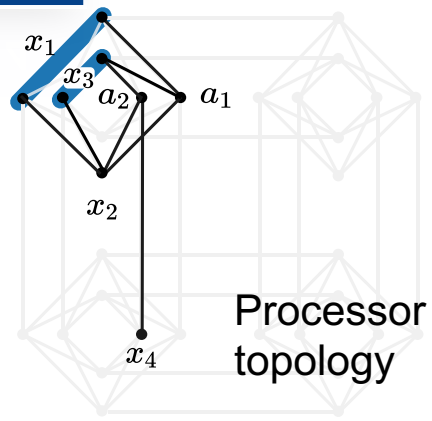
Objective function

Step 3



Problem graph

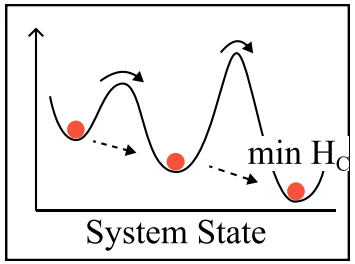
Step 4



Processor topology

Embedding

Step 5



Quantum Annealing

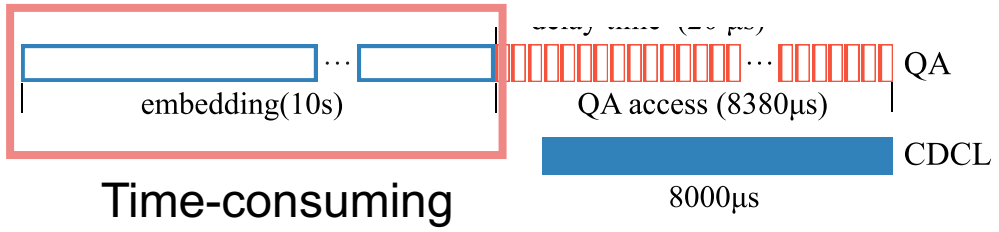
Step 6

$$min\ H_c(X, A) = 0$$
$$x_1 = x_2 = 0$$
$$x_3 = x_4 = 1$$

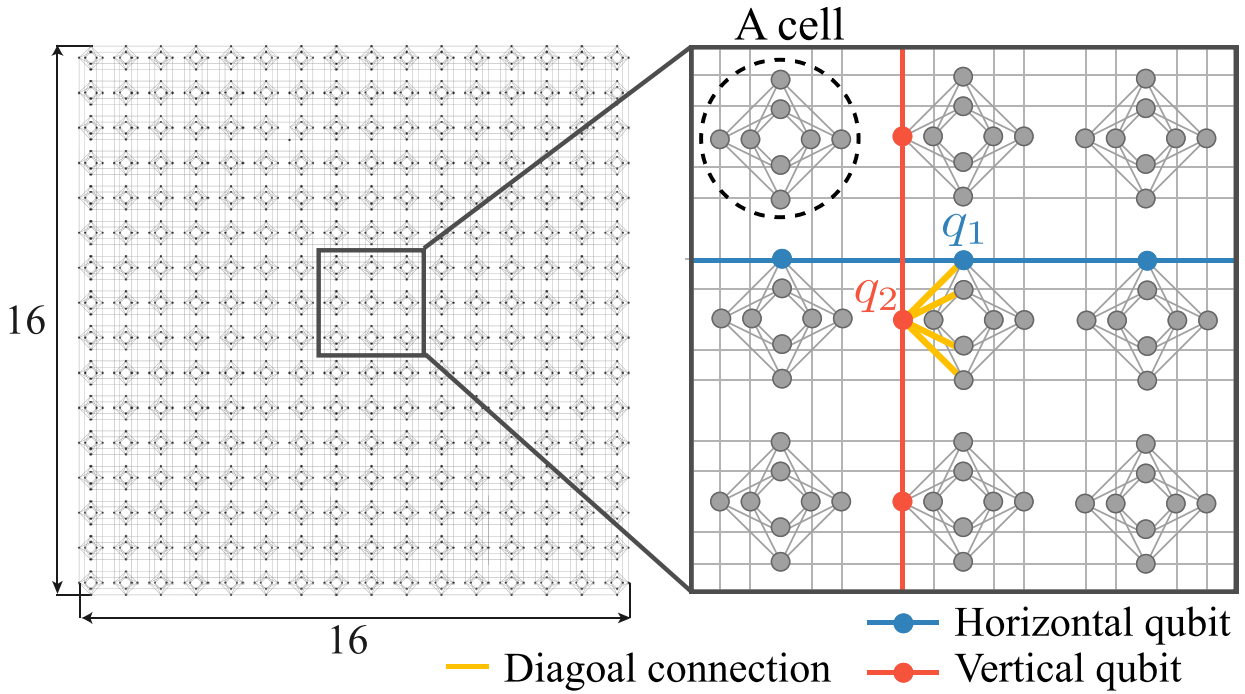
Solution

Challenge 1 of Quantum Annealing

High embedding latency



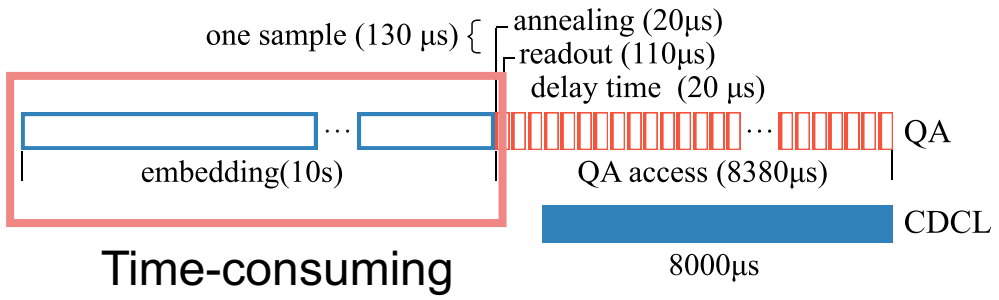
Time-consuming

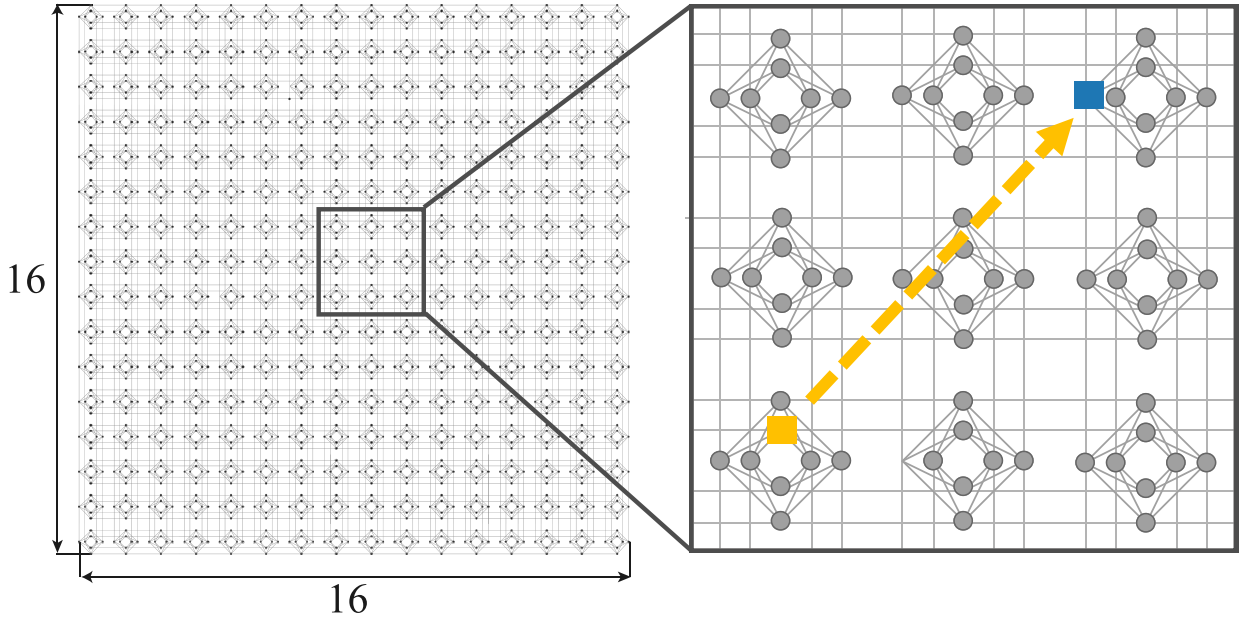


Processor topology of the D-Wave 2000Q

Challenge 1 of Quantum Annealing

High embedding latency

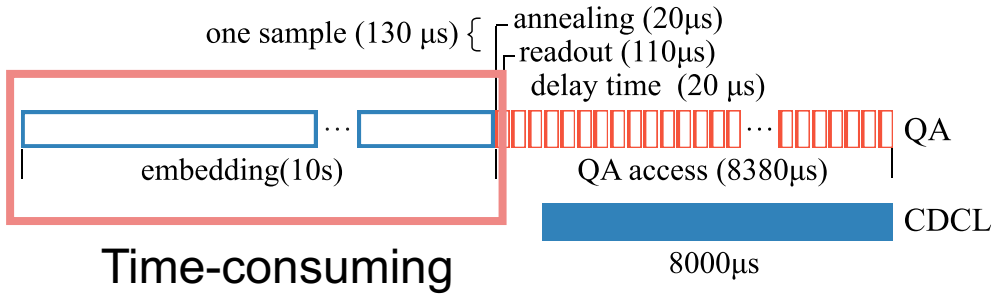


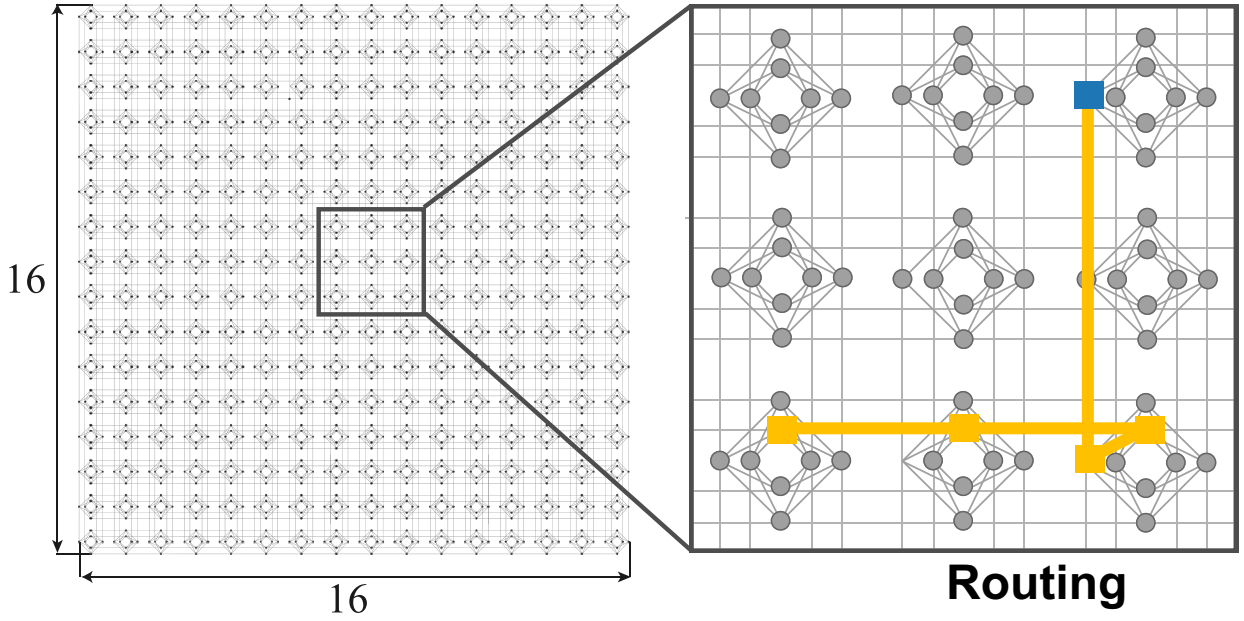


The two most time-consuming parts of the previous embedding schemes: **routing, adjustment**.

Challenge 1 of Quantum Annealing

High embedding latency





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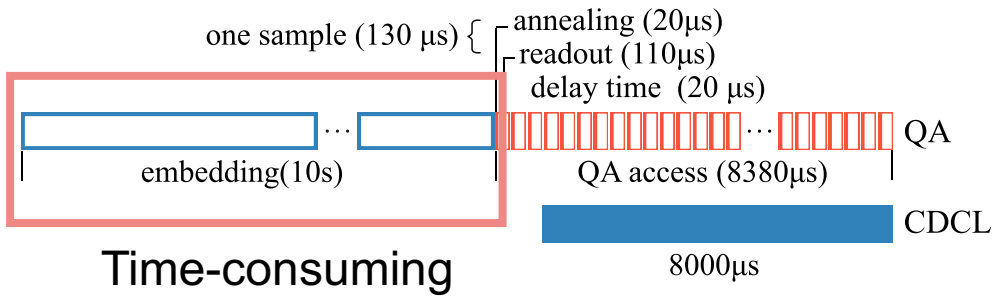
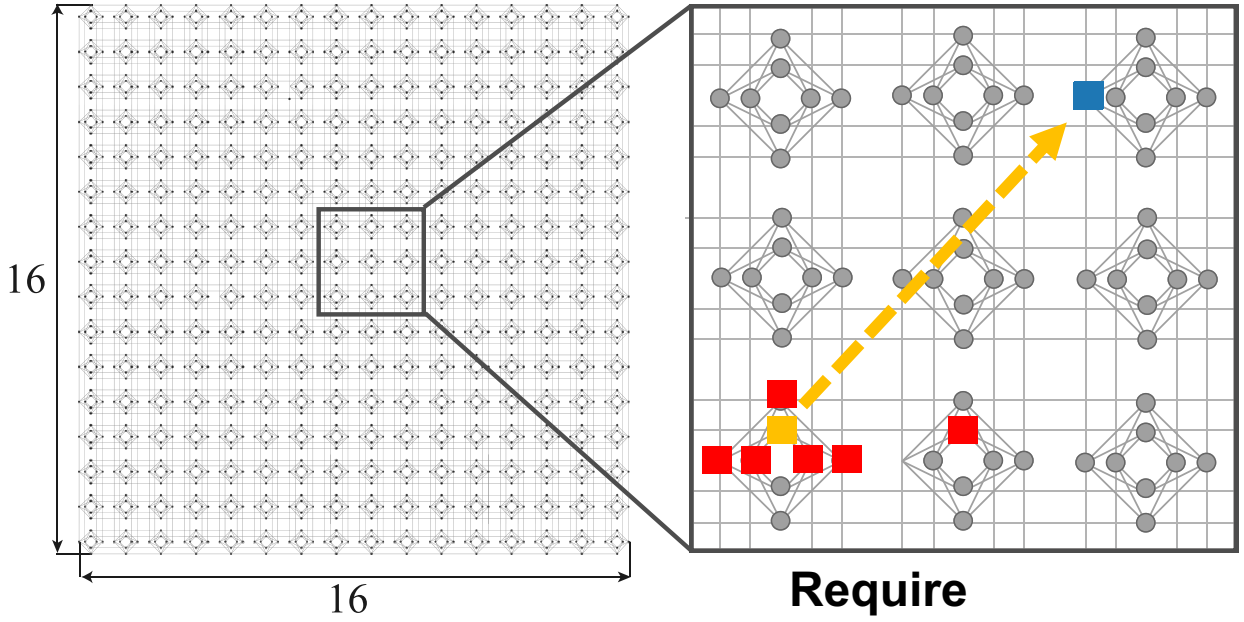
Challenge 1 of Quantum Annealing

High embedding latency



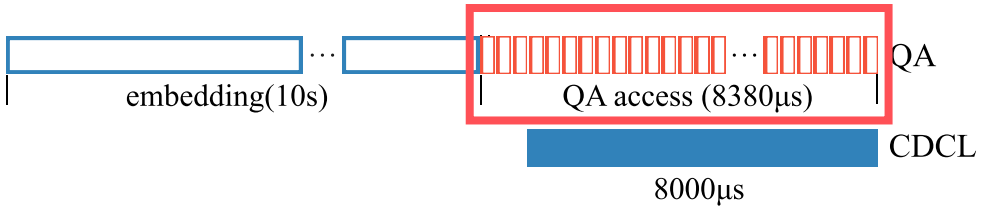


The two most time-consuming parts of the previous embedding schemes: **routing, adjustment**.

Challenge 2 of Quantum Annealing

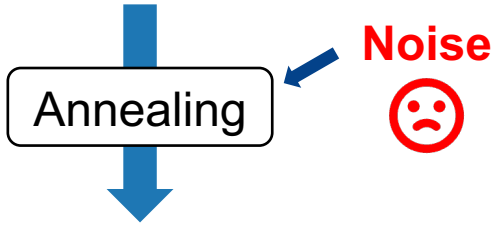
Noise

Require multiple executions



50 executions to find a solution for a 50-variable problem.

$$C = c_1 \wedge c_2$$
$$c_1 = x_1 \vee x_2 \vee x_3,$$
$$c_2 = \neg x_2 \vee \neg x_3 \vee x_4$$

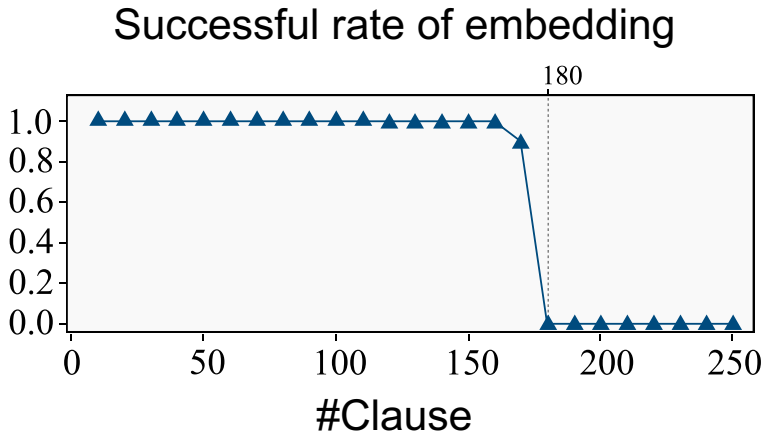


$$x_1 = x_2 = 0$$
$$x_3 = x_4 = 1$$

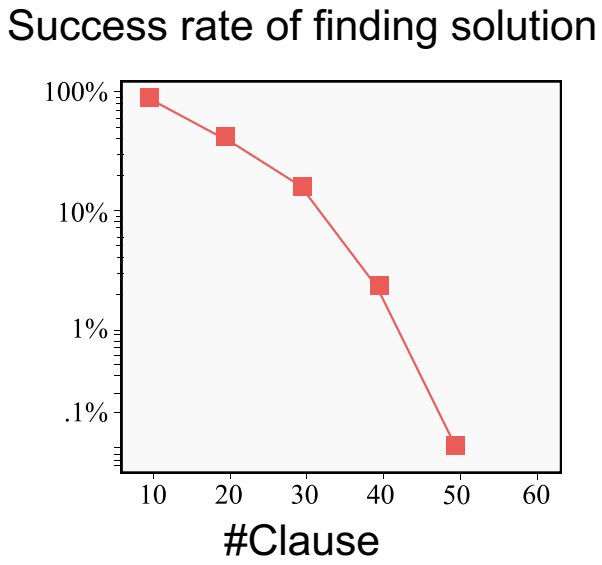
Some variables get wrong assignment.

Challenge 3 of QA: Limited Problem Scale

Limited Problem Scale



Limited by both the **number of qubits** and **noise**.

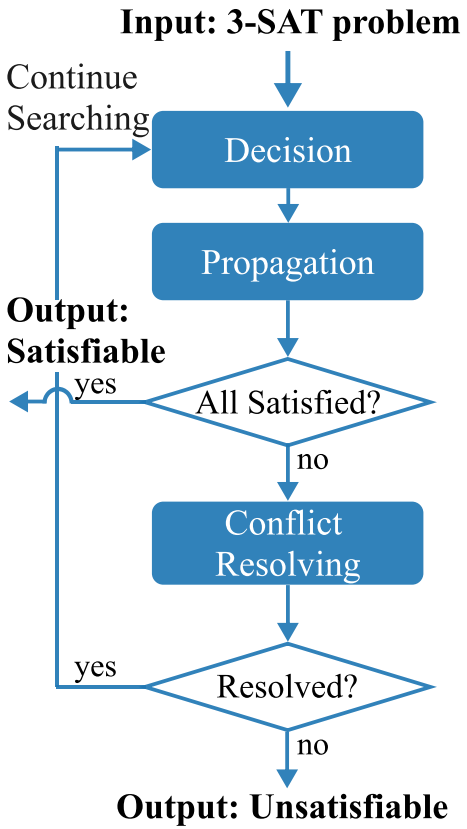


The success rate decreases **exponentially** as the problem size increases.

Outline of Presentation

- Background and challenges
- **HyQSAT overview**
- Frontend
- Backend
- Experiment
- API of HyQSAT

HyQSAT Workflow

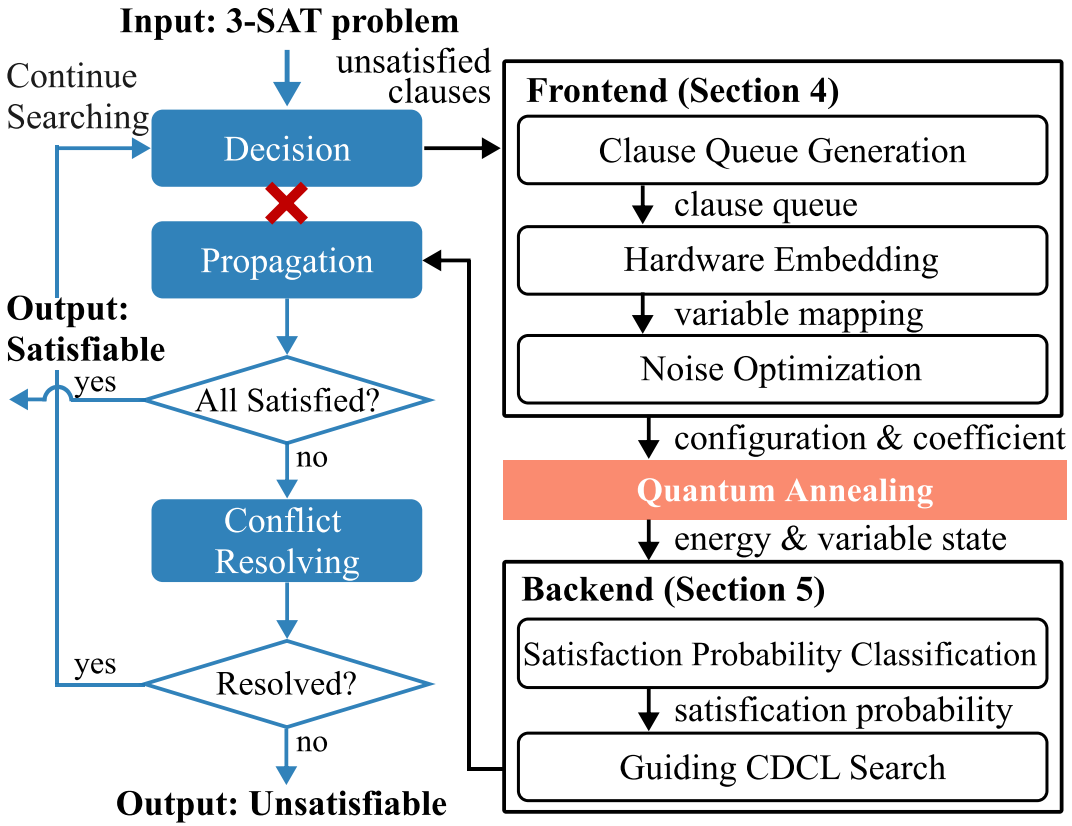


CDCL workflow

CDCL	Quantum Annealing
Large scale	Small scale
Difficulty in solving 'hard' clauses	Quantum speedup;
8000μs	**10s**+120μs

Caused by embedding

HyQSAT Workflow



HyQSAT workflow

CDCL	Quantum Annealing
Large scale	Small scale
Difficulty in solving 'hard' clauses	Quantum speedup;
8000μs	**10s**+120μs

Move critical clauses from CDCL to annealing:

1. **difficult for CDCL**
2. **efficiently embedded for quantum annealer**

Outline of Presentation

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- Experiment
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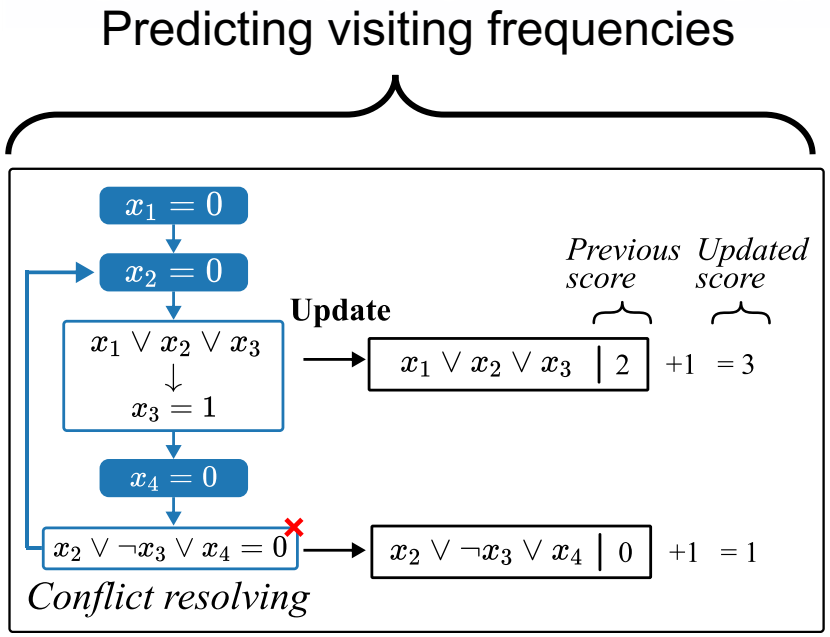
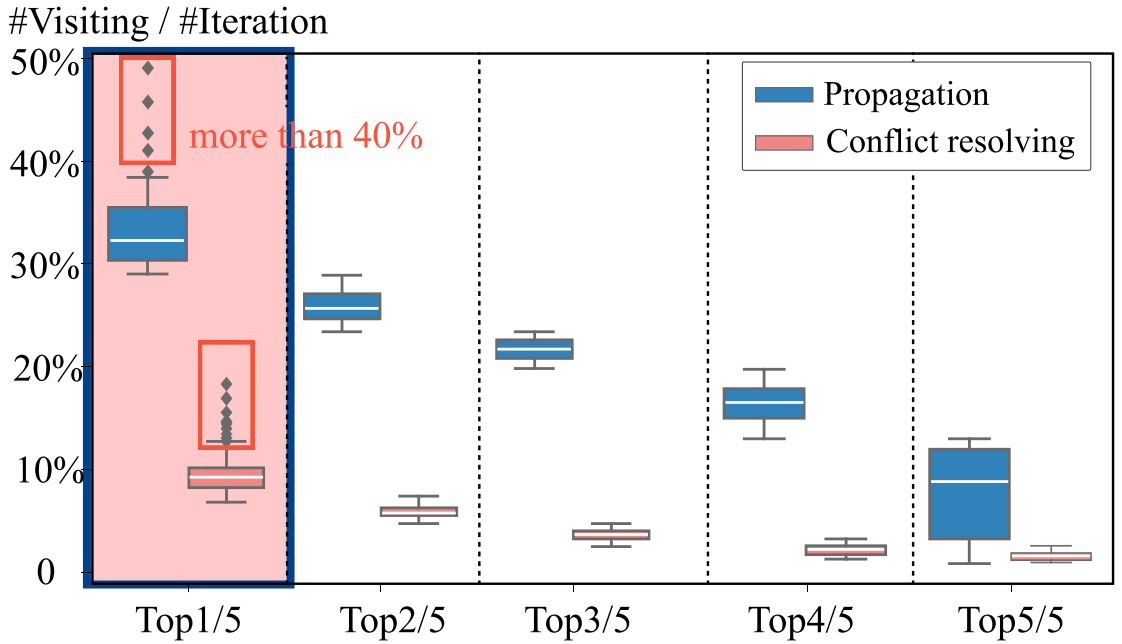
HyQSAT Frontend: Identify Difficult Clauses

☆ Clause visiting frequency = Difficulty

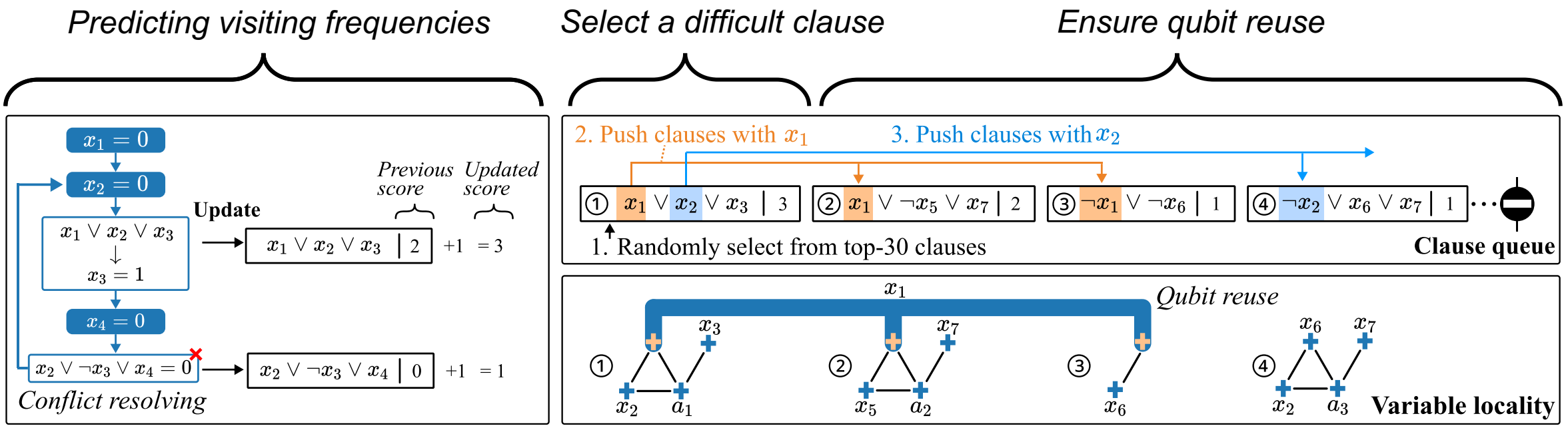


Define activity scores



Difficult clauses

HyQSAT Frontend: Identify Difficult Clauses

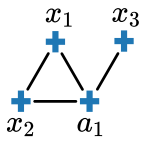
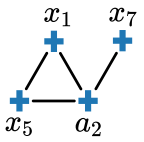
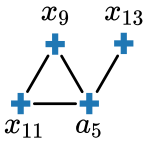


Define activity scores

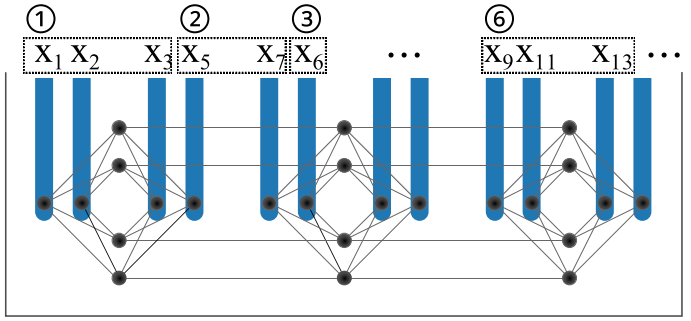
Apply breadth-first search among clauses with same variables

HyQSAT Frontend: Fast Embedding

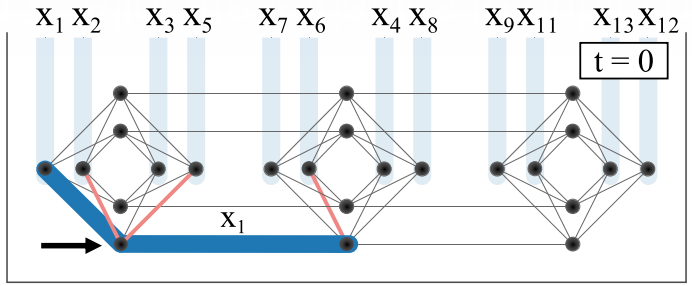
Step 1: Allocate variables to qubits of **vertical lines** according to their order in the clause queue

Clause:	① $x_1 \vee x_2 \vee x_3$	② $x_1 \vee \neg x_5 \vee x_7$	③ $\neg x_1 \vee \neg x_6$	⑥ $x_9 \vee x_{11} \vee x_{13}$
Problem graph:				
Connection requirement list:	x_1:{x_2} a_1:{x_1,x_2, x_3}	x_1:{x_2,x_5} a_1:{x_1,x_2,x_3} a_2:{x_1,x_5,x_7}	x_1:{x_2,x_5,x_6} a_1:{x_1,x_2,x_3} a_2:{x_1,x_5,x_7}	x_1:{x_2,x_5,x_6} a_1:{x_1,x_2,x_3} a_2:{x_1,x_5,x_7} … a_5:{x_9,x_{11},x_{13}}

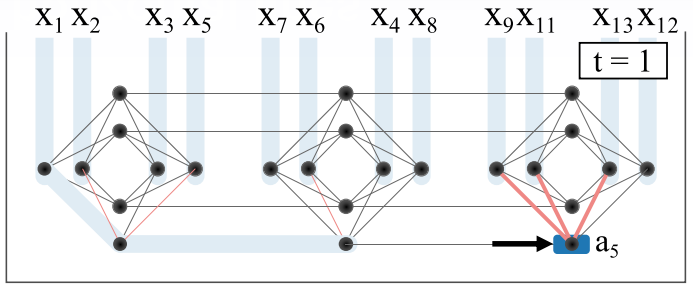
gathered for allocation together



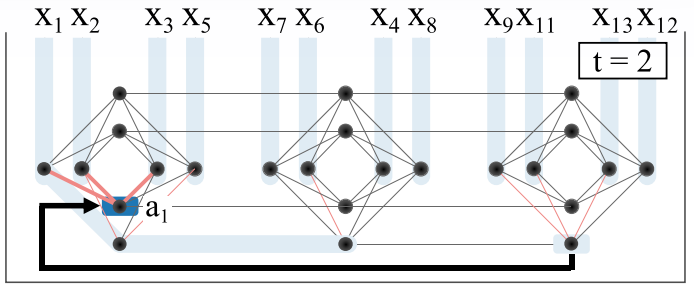
Step 2: Allocate variables to qubits of **horizontal lines**



x_1 :{x_2, x_5, x_6}



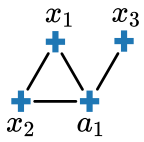
a_5 :{x_9, x_{11}, x_{13}}



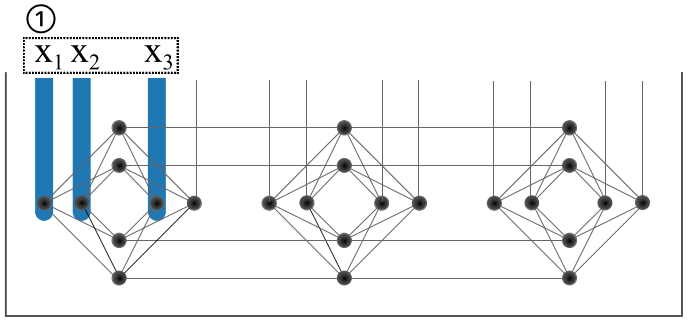
a_1 :{x_1, x_2, x_3}

HyQSAT Frontend: Fast Embedding

Step 1: Allocate variables to qubits of **vertical lines** according to their order in the clause queue

Clause:	① $x_1 \vee x_2 \vee x_3$
Problem graph:	
Connection requirement list:	x_1:{x_2} a_1:{x_1,x_2, x_3}

gathered for allocation together



HyQSAT Frontend: Fast Embedding

Step 1: Allocate variables to qubits of **vertical lines** according to their order in the clause queue

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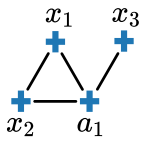
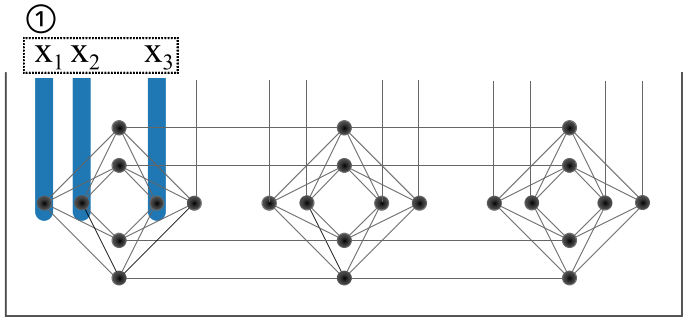
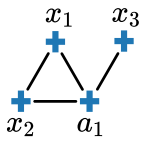
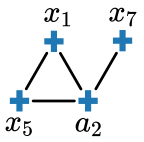
Problem graph:	
Connection requirement list:	x_1:{x_2} a_1:{x_1,x_2, x_3}

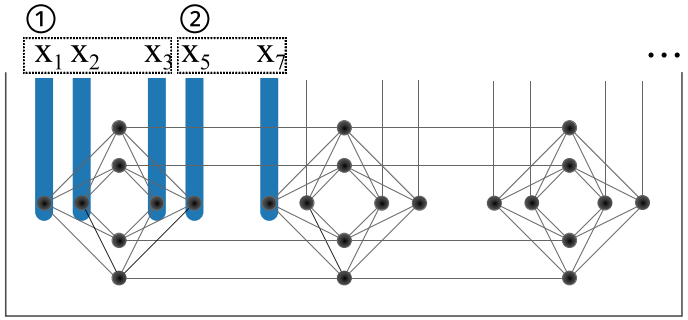
gathered for allocation together



HyQSAT Frontend: Fast Embedding

Step 1: Allocate variables to qubits of **vertical lines** according to their order in the clause queue

Clause:	① $x_1 \vee x_2 \vee x_3$	② $x_1 \vee \neg x_5 \vee x_7$
Problem graph:		
Connection requirement list:	x_1:{x_2} a_1:{x_1,x_2, x_3}	x_1:{x_2,x_5} a_1:{x_1,x_2,x_3} a_2:{x_1,x_5,x_7}



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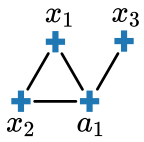
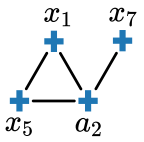
Problem graph:			
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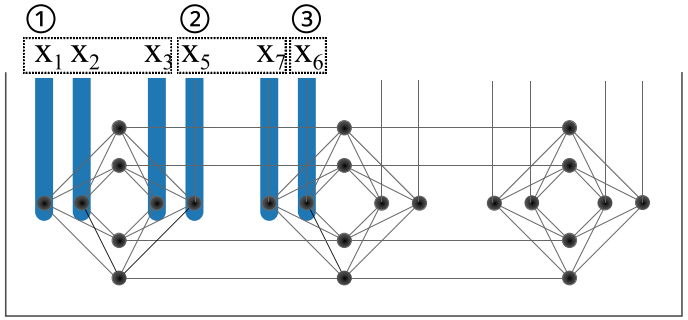

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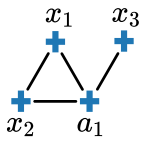
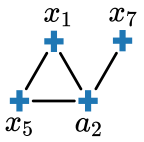
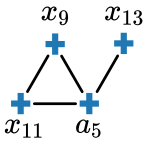
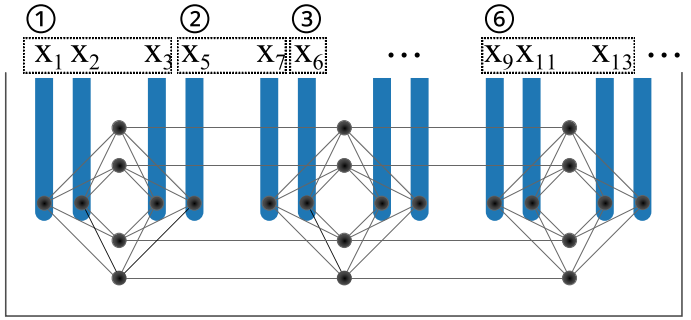
Problem graph:				
Connection requirement list:	x_1:{x_2} a_1:{x_1,x_2, x_3}	x_1:{x_2,x_5} a_1:{x_1,x_2,x_3} a_2:{x_1,x_5,x_7}	x_1:{x_2,x_5,x_6} a_1:{x_1,x_2,x_3} a_2:{x_1,x_5,x_7}	x_1:{x_2,x_5,x_6} a_1:{x_1,x_2,x_3} a_2:{x_1,x_5,x_7} … a_5:{x_9,x_{11},x_{13}}



HyQSAT Frontend: Fast Embedding

Step 1: Allocate variables to qubits of **vertical lines** according to their order in the clause queue

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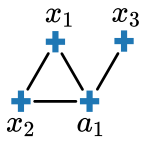
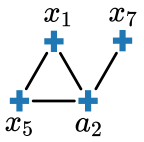
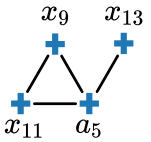
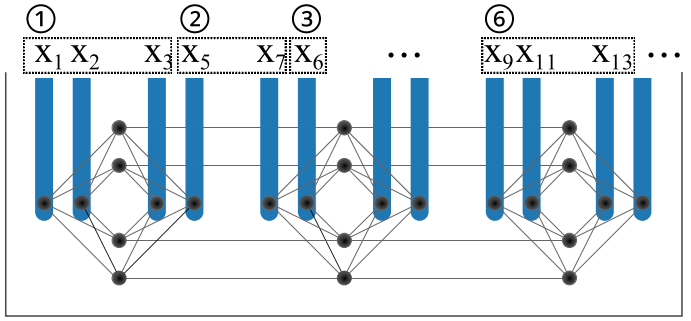
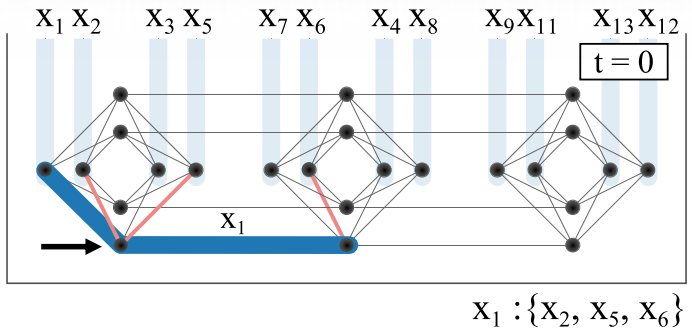
Problem graph:				
Connection requirement list:	x_1:{x_2} a_1:{x_1,x_2, x_3}	x_1:{x_2,x_5} a_1:{x_1,x_2,x_3} a_2:{x_1,x_5,x_7}	x_1:{x_2,x_5,x_6} a_1:{x_1,x_2,x_3} a_2:{x_1,x_5,x_7}	x_1:{x_2,x_5,x_6} a_1:{x_1,x_2,x_3} a_2:{x_1,x_5,x_7} … a_5:{x_9,x_{11},x_{13}}



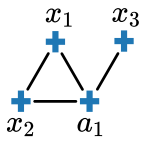
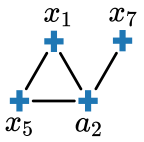
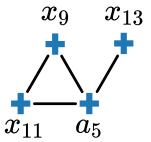
Step 2: Allocate variables to qubits of **horizontal lines**

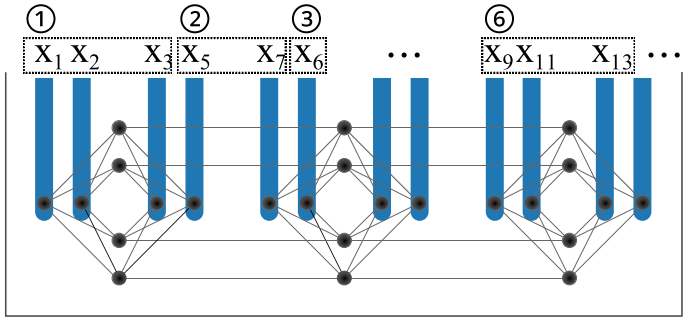


x_1 :{x_2, x_5, x_6}

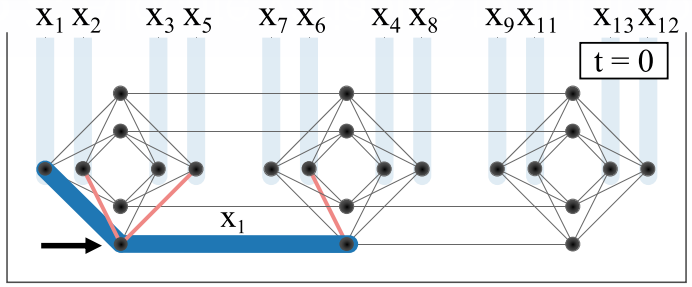
HyQSAT Frontend: Fast Embedding

Step 1: Allocate variables to qubits of **vertical lines** according to their order in the clause queue

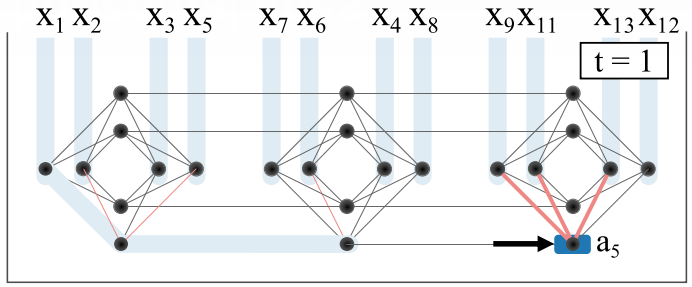
Clause:	① $x_1 \vee x_2 \vee x_3$	② $x_1 \vee \neg x_5 \vee x_7$	③ $\neg x_1 \vee \neg x_6$	⑥ $x_9 \vee x_{11} \vee x_{13}$
Problem graph:				
Connection requirement list:	x_1:{x_2} a_1:{x_1,x_2, x_3}	x_1:{x_2,x_5} a_1:{x_1,x_2,x_3} a_2:{x_1,x_5,x_7}	x_1:{x_2,x_5,x_6} a_1:{x_1,x_2,x_3} a_2:{x_1,x_5,x_7}	x_1:{x_2,x_5,x_6} a_1:{x_1,x_2,x_3} a_2:{x_1,x_5,x_7} … a_5:{x_9,x_{11},x_{13}}



Step 2: Allocate variables to qubits of **horizontal lines**



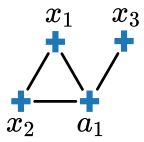
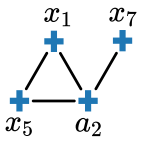
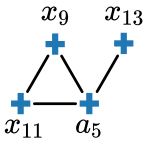
x_1 :{x_2, x_5, x_6}



a_5 :{x_9, x_{11}, x_{13}}

HyQSAT Frontend: Fast Embedding

Step 1: Allocate variables to qubits of **vertical lines** according to their order in the clause queue

Clause:	① $x_1 \vee x_2 \vee x_3$	② $x_1 \vee \neg x_5 \vee x_7$	③ $\neg x_1 \vee \neg x_6$	⑥ $x_9 \vee x_{11} \vee x_{13}$
Problem graph:				
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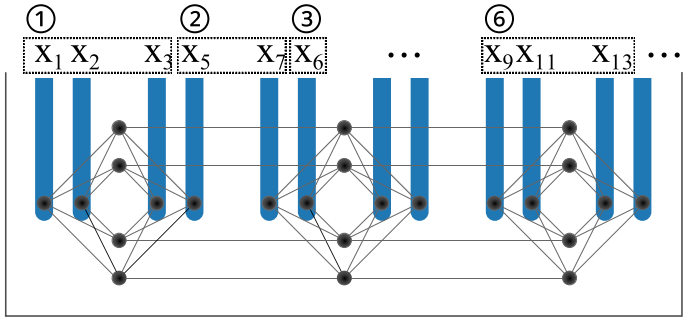

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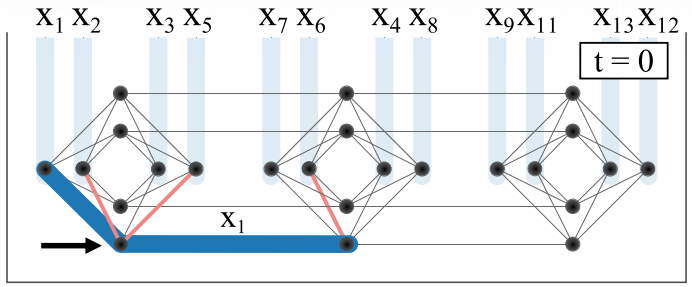

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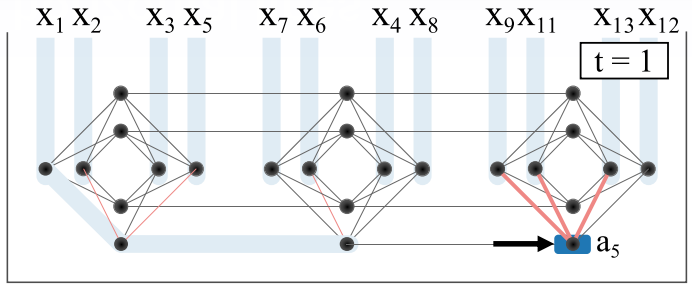

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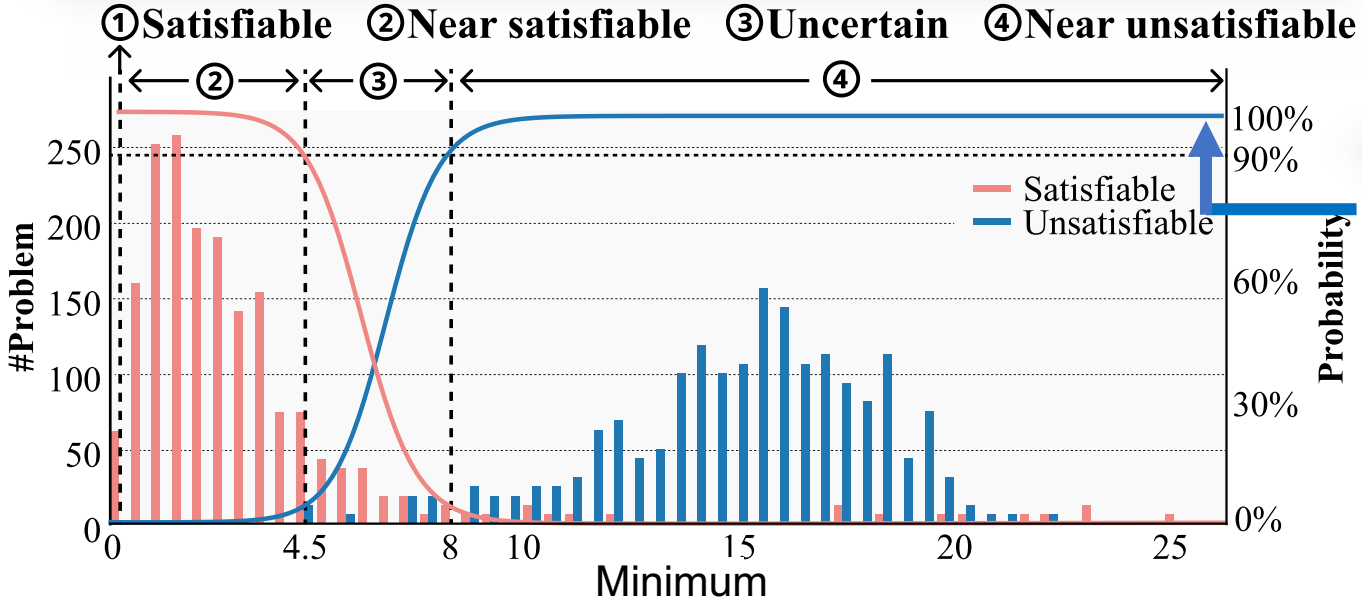
Outline of Presentation

- Background and challenges
- HyQSAT overview
- Frontend
- **Backend**
- Experiment
- API of HyQSAT

HyQSAT Backend: Satisfaction Probability Classification

Quantum annealing

Minimum value of objective function, Possible solution



Based on the noise model of D-Wave 2000Q

Gaussian Naive Bayes model to estimate the probability of satisfaction

① Satisfiable problem: [0, 0].

② Near satisfiable problem: (0, 4.5].

③ Uncertain problem: (4.5, 8].

④ Near unsatisfiable problem: (8, +∞].

HyQSAT Backend: Guiding CDCL Search

Depending on **the number of embedded clauses and their satisfaction probability**, we divide them into **four cases** and propose several feedback strategies to prune the CDCL search space.

<table>
<tr><th></th><th>Satisfiable</th><th>Near satisfiable</th><th>Uncertain</th><th>Near unsatisfiable</th></tr>
<tr><td>All embedded</td><td>Strategy 1</td><td rowspan="2">Strategy 2</td><td rowspan="2">Strategy 3</td><td rowspan="2">Strategy 4</td></tr>
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</table>

Contribute to no acceleration for the classic CDCL.

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Not all embedded				

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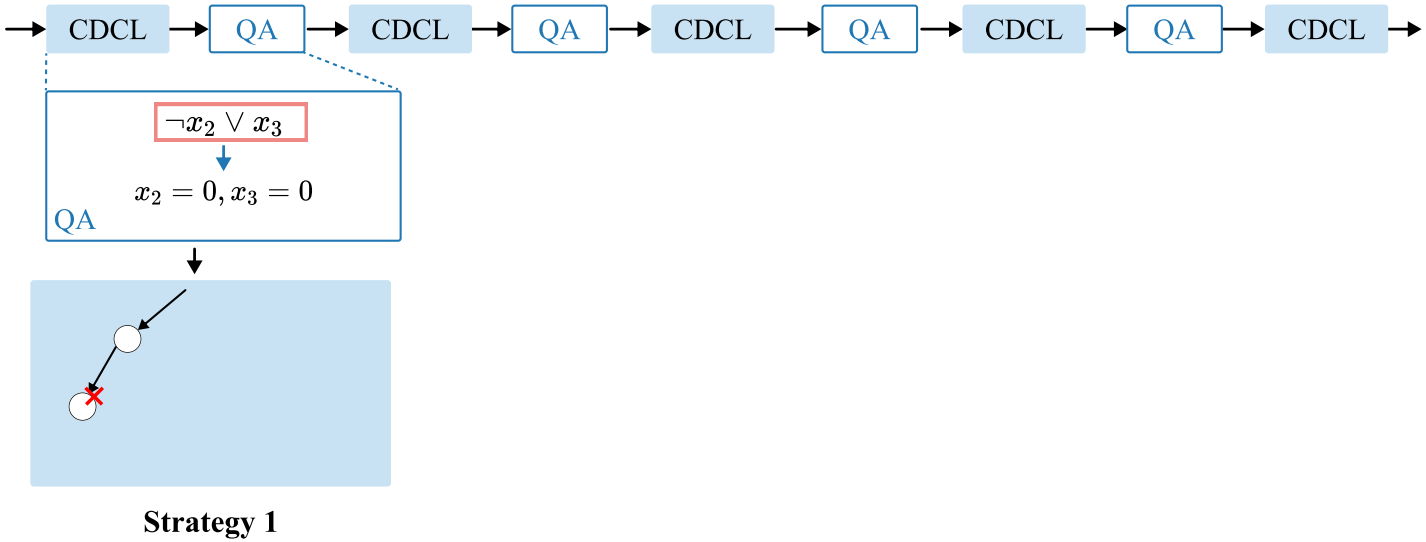
Feedback strategy 1, 2, 4



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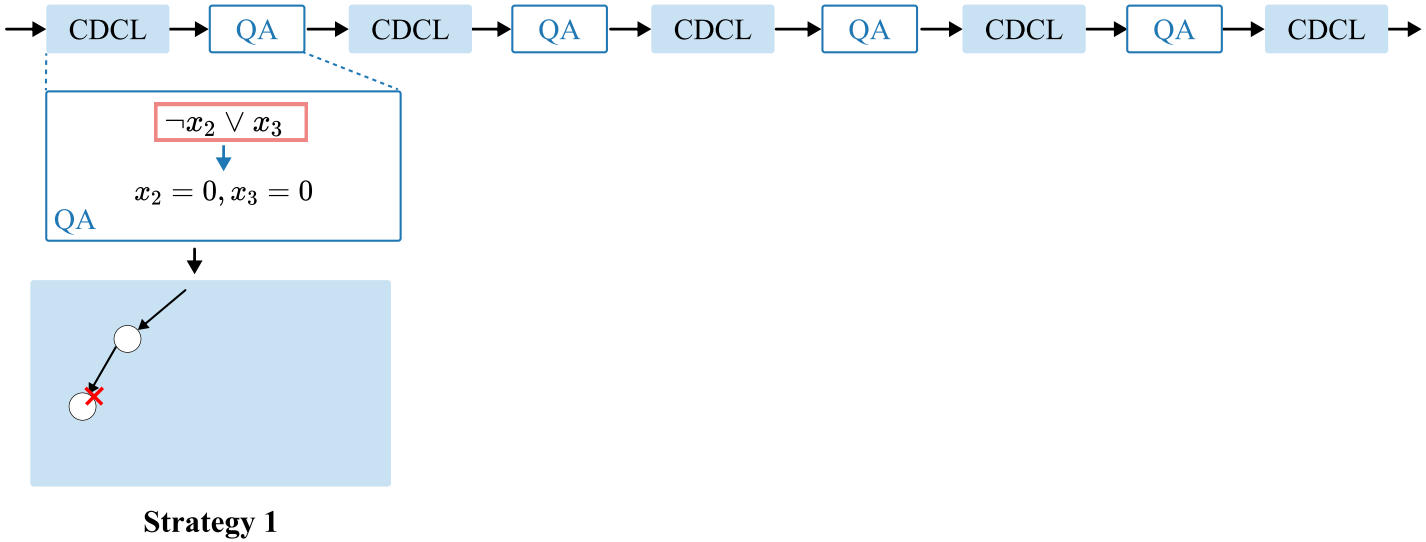

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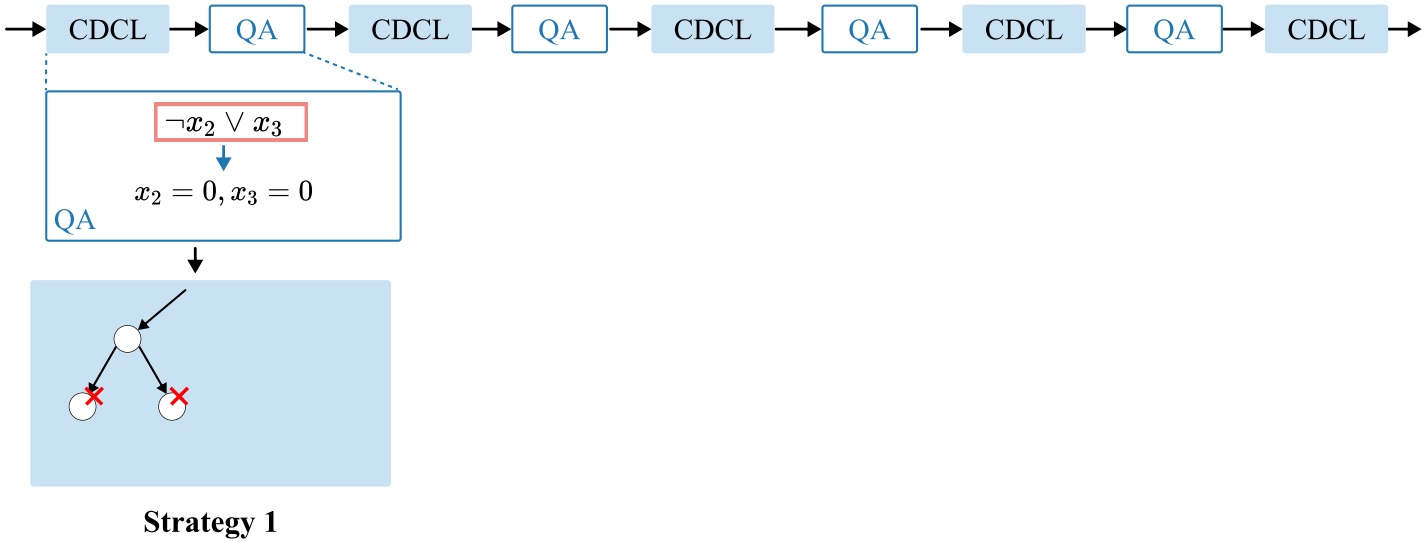

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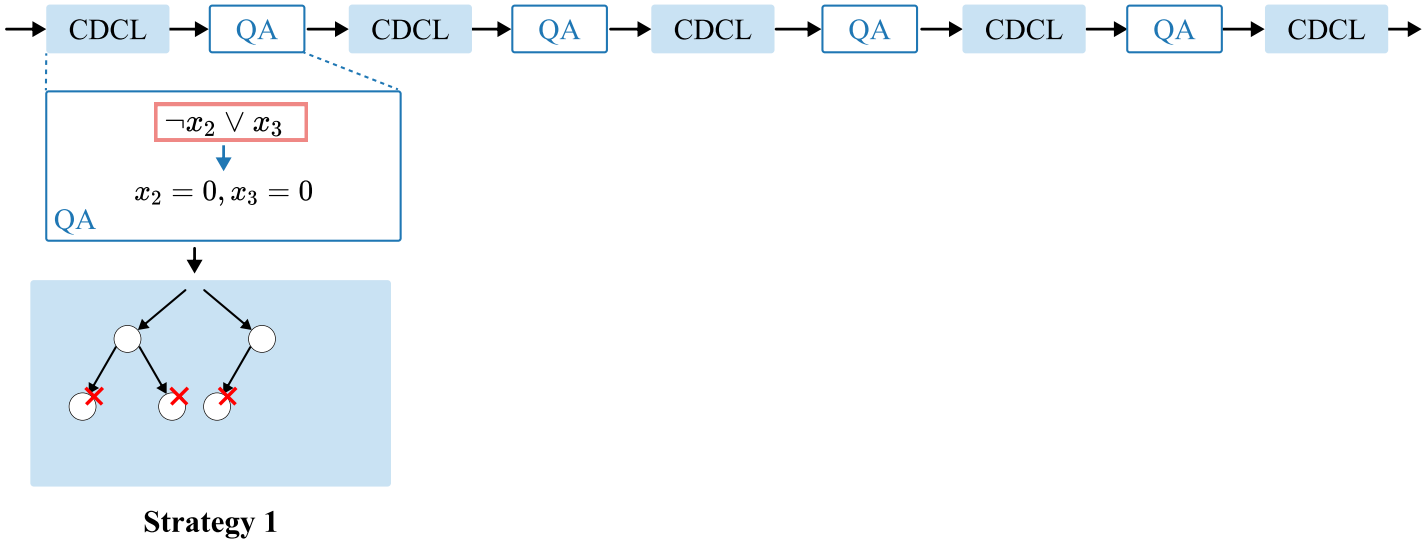

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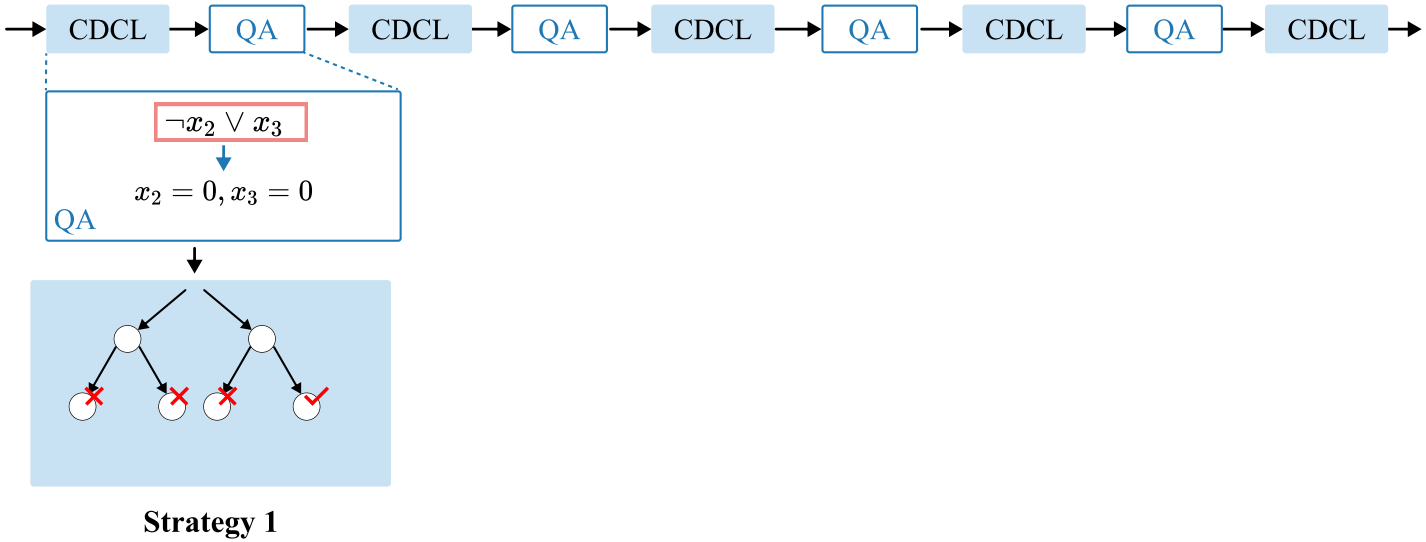

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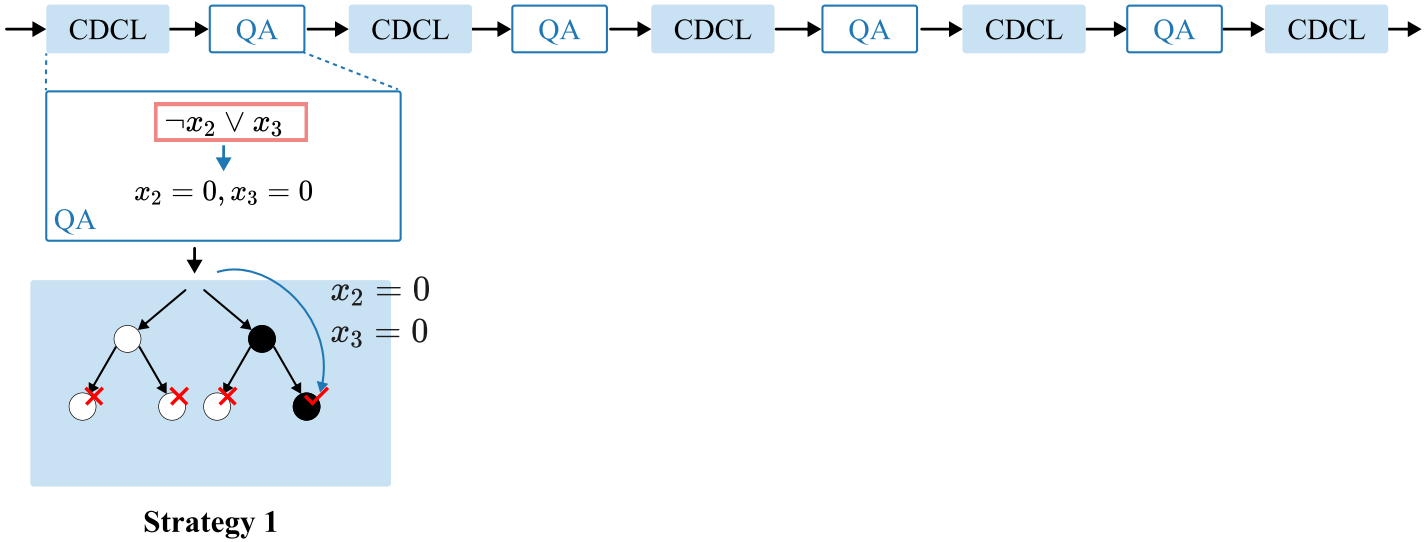

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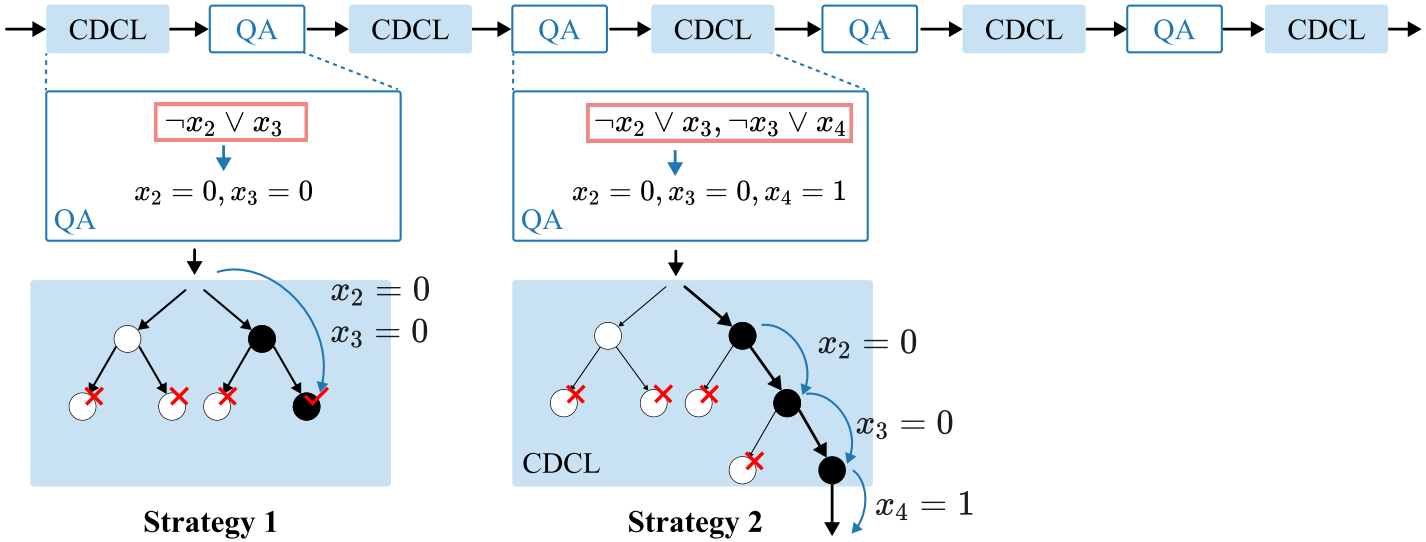

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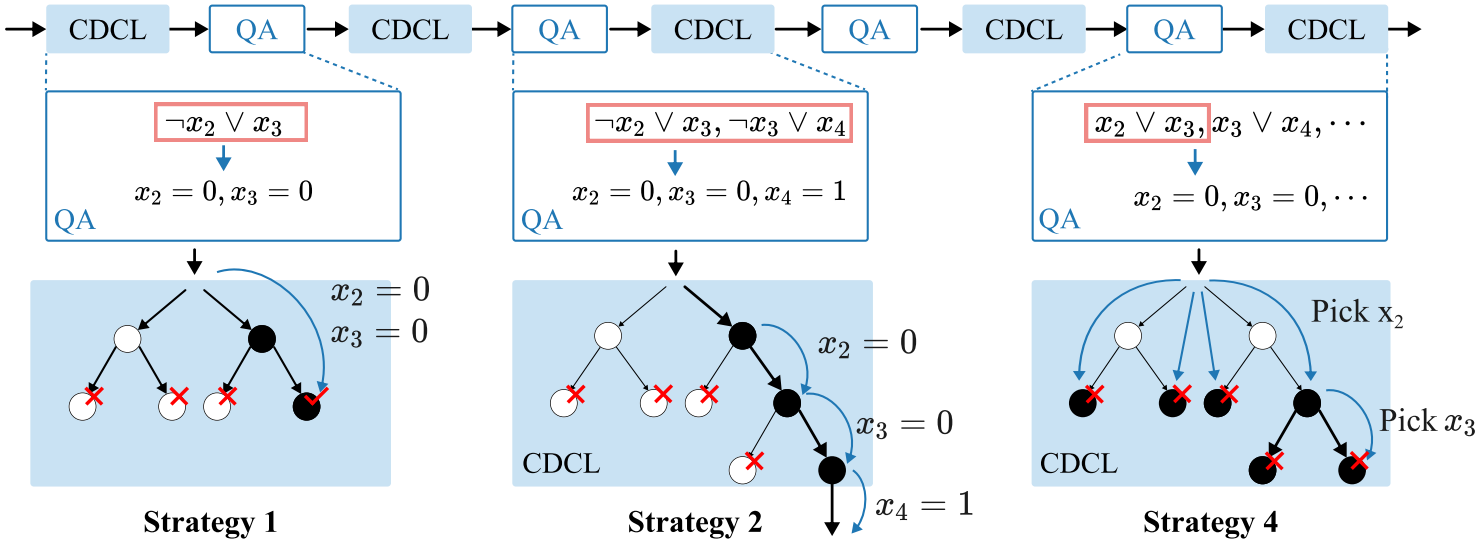

Outline of Presentation

- Background and challenges
- HyQSAT overview
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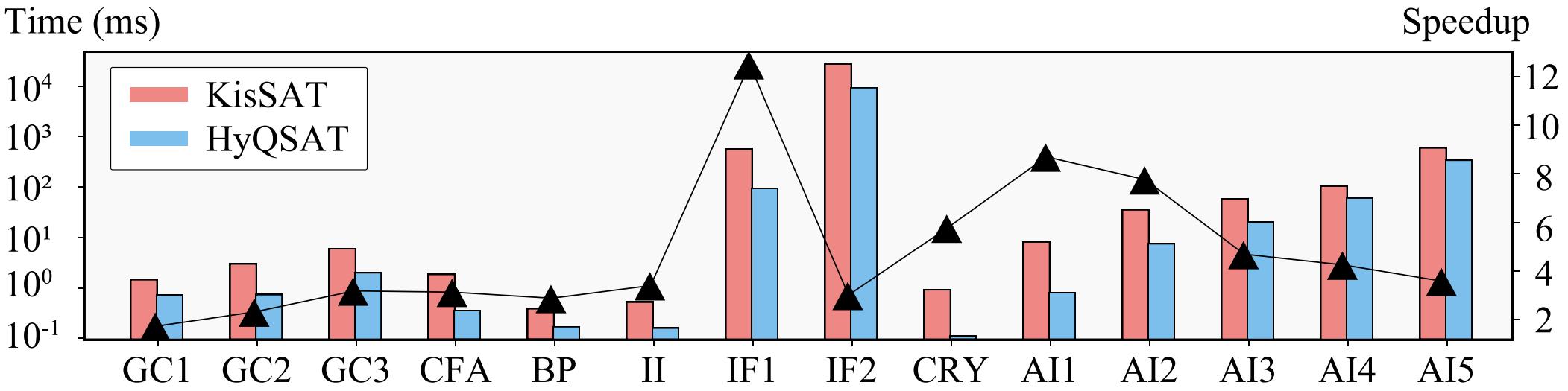
- Backend
- **Experiment**
- API of HyQSAT

Evaluation on the Real-World Quantum Annealer



graph coloring (CG), circuit fault analysis (CFA), block planning (BP), inductive inference (II), integer factorization (IF), cryptography (CRY), and artificial intelligence (AI)

- **7 domains, 11 benchmarks**
- **D-Wave 2000Q real-world quantum annealer**
- **4.92X speedup compared to KisSAT (win SAT competition 2022)**

Outline of Presentation

- Background and challenges
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- **API of HyQSAT**

API of Janus-SAT

File:
- examples/4-1.solve_sat_domain_problem.ipynb
- https://janusq.github.io/tutorials/Demonstrations/4-1.solve_sat_domain_problem

Import package and data

Configure the solver

Solve the problem

```
from janusq.hyqsat import solve_by_janusct


# input cnf flie
file_path = "cnf_examples/uf50-01.cnf"
# if verbose
verbose = True
# cpuLim time (s). 0 means infinite
cpu_lim = 0
# memLim . 0 means infinite
mem_lim = 0

result_janus = solve_by_janusct(file_path, verb=
verbose, cpu_lim=cpu_lim, mem_lim=mem_lim)
```

加下配置的解释

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```

换个大点的数据集

Output:

```
{
        'restarts': 1,
        'conflicts': 9,
        'conflict cost': 0.054,
        'decisions': 0,
        'propagations': 0,
        'conflict literals': 37,
        'solving time': 0.355,
        'annealing time': 0.0,
        'quantum count': 0,
        'simulate time': 1.07241,
        'quantum success number': 9,
        'quantum conflict number': 13,
        'quantum one time solve number': 0,
        'isSatisfiable': True,
}
```

API of Janus-SAT

Solving 3-SAT problems on real-world quantum annealer.

Import package and data

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真机的例子

Thanks for listening

HyQSAT: A Hybrid Approach for 3-SAT Problems by Integrating Quantum Annealer with CDCL

Siwei Tan , Mingqian Yu , Andre Python , Yongheng Shang , Tingting Li , Liqiang Lu*, and Jianwei Yin*