命题逻辑

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华东师范大学

灵感来源于生活

- 人是动物
- 小孩是人
- 小孩是动物?

- 如果今天下雨我就在家里
- 今天下雨
- 我在家里

灵感来源于生活

- 人是动物
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- 小孩是动物?

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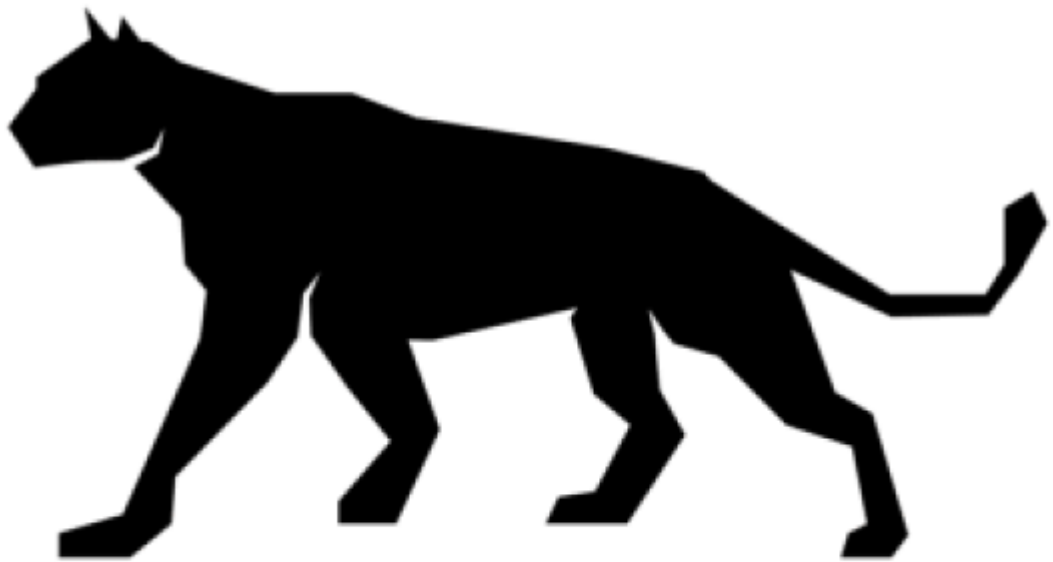
我们是如何做推理的?

剧本杀初级版

- 爱丽丝、爱丽丝的丈夫、他们的儿子、女儿和爱丽丝的兄弟卷入了一起谋杀案。 五人中的一人杀死了另外四人中的一人。 以下事实与提到的五个人有关:
  1. 案发时，一男一女在一家酒吧里。
  2. 谋杀案发生时，受害者和凶手一起在海滩上。
  3. 谋杀发生时，爱丽丝的两个孩子中的一个独自一人。
  4. 爱丽丝和她的丈夫在谋杀发生时并不在一起。
  5. 受害者的双胞胎不是凶手。
  6. 凶手比受害者年轻。
- 五人中的哪一位是受害者?

The Lady and the Tiger

- Two doors containing either Ladies or Tigers



The Lady and the Tiger

- You will be shown two doors, to two rooms.
  - Each could contain either a lady or a tiger . . .
  - It could be that **both** rooms contain a lady, or that **both** rooms contain a tiger!

The Lady and the Tiger

Q1

One of these is true…

In this room, there is a lady, and in the other room there is a tiger.

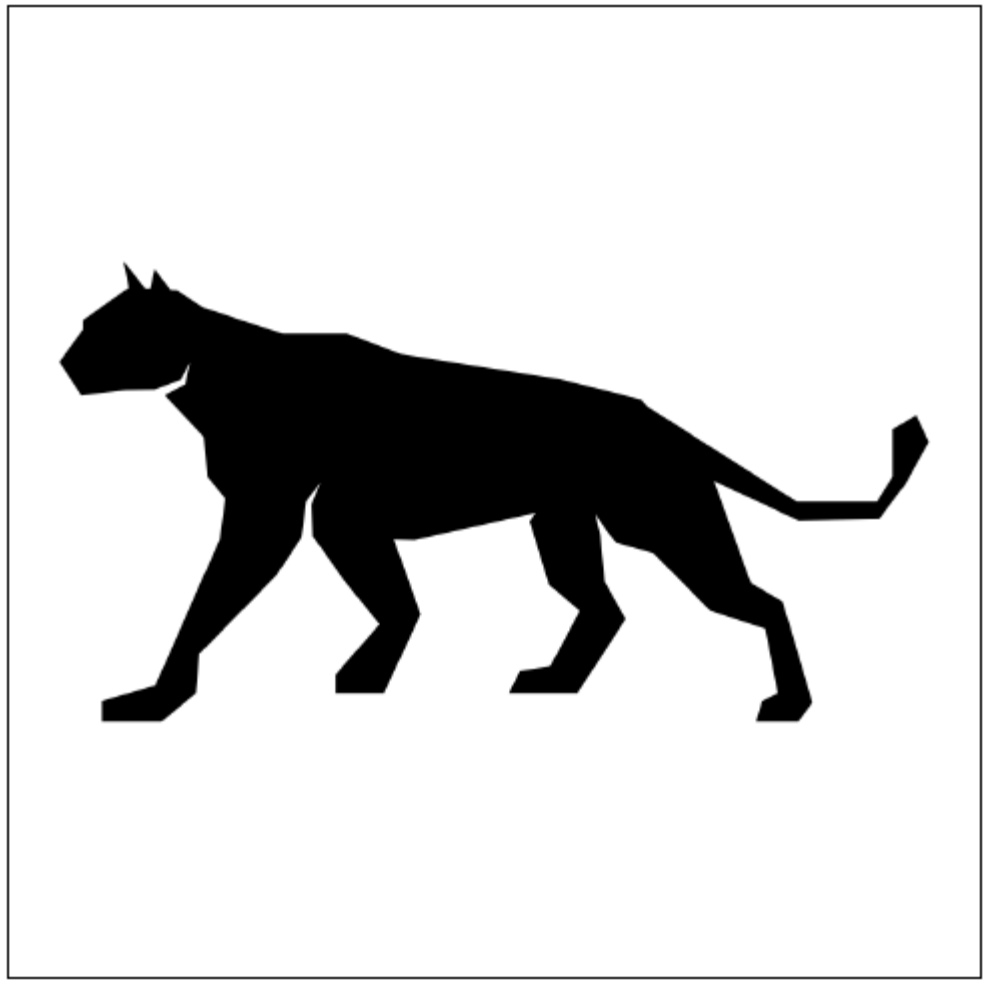
The other is false…

In one of these rooms there is a lady, and in one of these rooms there is a tiger.

The Lady and the Tiger

Q1

One of these is true…



The other is false…

布尔逻辑公式

1. 一个布尔原子$p \in \{0,1\}$是一个布尔逻辑公式;

2. 如果φ是一个布尔逻辑公式，那么$(\varphi), \neg\varphi, \varphi\&\varphi, \varphi|\varphi, \varphi \Rightarrow \varphi, \varphi \Leftrightarrow \varphi$也是布尔逻辑公式。

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a | (b & c)

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a | (b & c)

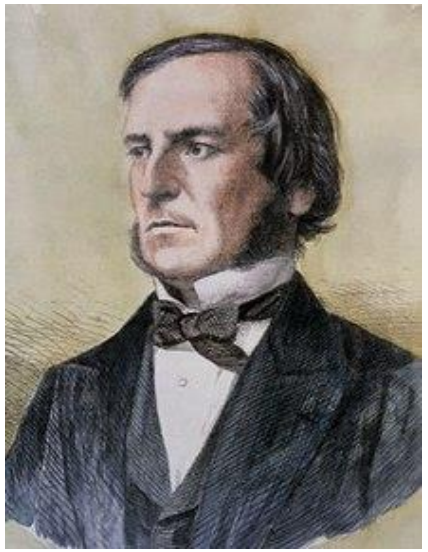
(a | c) & (¬a | ¬c)

思考

给定一个字符串，如何判定它是否是一个布尔逻辑公式?

布尔逻辑的历史

G. W. Leibniz
(1646 - 1716)



George Boole
(1815 - 1864)

Augustus De Morgan
(1806 - 1871)

The craters Boole and De Morgan on the Moon are named after them.

布尔逻辑公式的解

给布尔公式中每个变量赋值0或1，若可以使得公式最后赋值为1，那么变量赋值的组合就称为它的一个解。

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a | (b & c)

{a=1, b = 1, c = 1}

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a | (b & c)

{a=1, b = 1, c = 1}

(a | c) & (¬a | ¬c)

{a=1, c=0}

课堂练习

请给出一下布尔公式的一个解：

(1) (a | b) & (!a | ! b)
(2) (a & !b) -> (b & !c)
(3) (a & b) -> ((b | !c) & (a &!b & c))

布尔公式求解

a	b	c	a | (b & c)
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	1
1	0	1	1
1	1	0	1
1	1	1	1

真值表法：采用穷举思想

布尔公式求解

a	b	c	a | (b & c)
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	1
1	0	1	1
1	1	0	1
1	1	1	1

真值表法：采用穷举思想

状态空间爆炸!

练习

用真值表给出布尔逻辑公式(a & b) -> ((b | !c) & (a &!b & c))的解。

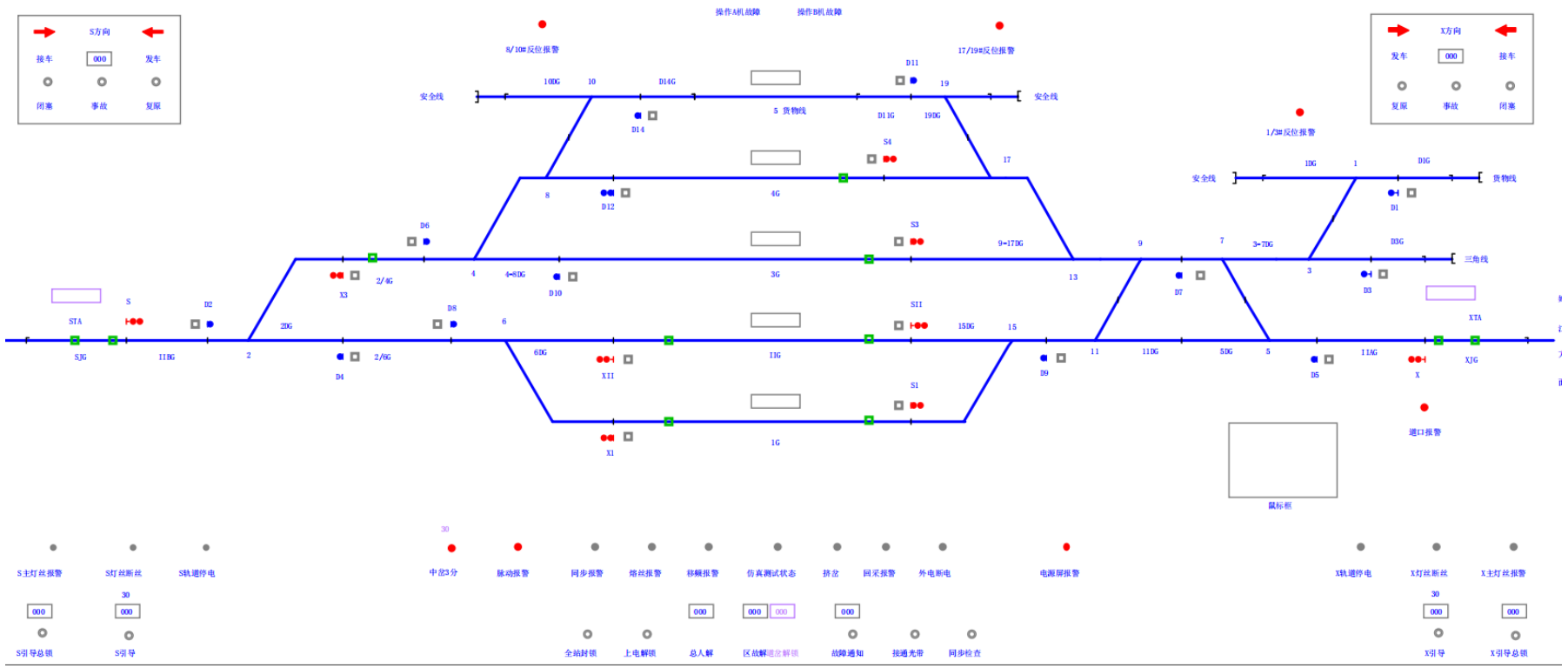
思考题

- 如何求解一个布尔公式的所有解?
- 如何高效的求解一个布尔公示的所有解?

从布尔逻辑公式到硬件电路（1940）

底层电路都是布尔逻辑。

信号系统



S方向
接车
000
发车
闭塞
事故
复原
操作A机故障
操作B机故障
8/10#反位报警
17/19#反位报警
安全线
5 货物线
1/3#反位报警
X方向
发车
000
接车
复原
事故
闭塞
安全线
货物线
三角线
STA
S
D2
D6
D8
D4
D10
D12
D14
D11
D1
D3
D5
D7
D9
X3
X1
X
XTA
XJG
S3
S4
S1
S11
1G
3G
4G
6DG
11G
15DG
9-17DG
3-7DG
2DG
2/4G
2/6G
4-8DG
10DG
19DG
1DG
11DG
5DG
11AG
S主灯丝报警
S灯丝断丝
S轨道停电
中岔3分
脉动报警
同步报警
熔丝报警
移频报警
仿真测试状态
挤岔
回采报警
外电断电
电源屏报警
X轨道停电
X灯丝断丝
X主灯丝报警
S引导总锁
S引导
全站封锁
上电解锁
总人解
区故解
故障通知
接通光带
同步检查
X引导
X引导总锁

The Lady and the Tiger

Q2

Either both signs are false…

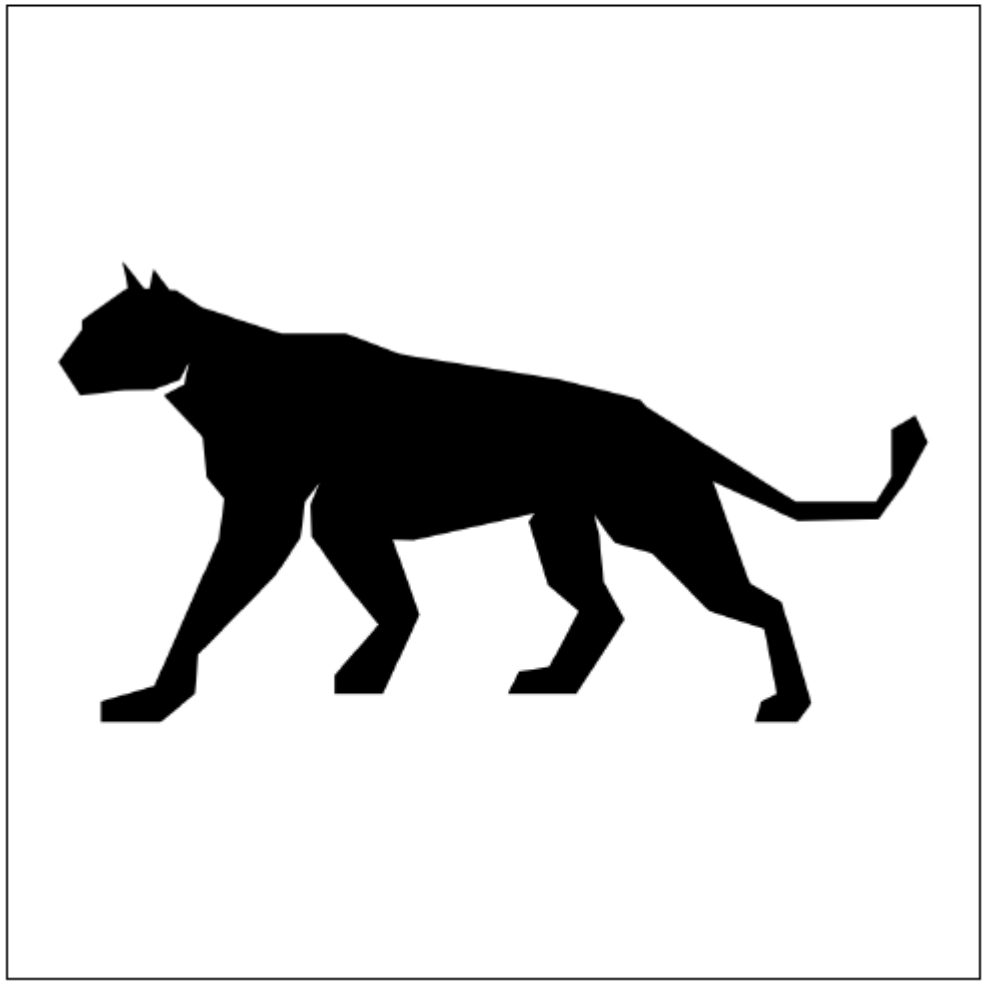
At least one of these rooms contains a lady

Or both are true…

A tiger is in the other room…

The Lady and the Tiger
Q2

Either both signs are false…



Or both are true…

The Lady and the Tiger

Q3

Either both signs are false…

Either a tiger is in this room, or a lady is in the other room.

Or both are true…

An lady is in the other room.

The Lady and the Tiger

Q3

Either both signs are false…

Or both are true…

The Lady and the Tiger

- Once again, you'll have to tell Ladies from Tigers
- A new twist is being added.
  - Two doors
  - If a lady is in Room I, then the sign on the door is true. If a tiger is in Room I, then the sign on the door is false.
  - The opposite is true for Room II.

  - **Problem… the signs fell off the doors. We can't remember which one goes where!!!**

The Lady and the Tiger

Q1

Room ??

This room contains a tiger.

Room ??

Both rooms contain tigers

The Lady and the Tiger

Q1

Room II

Room I

The Lady and the Tiger

- Once again, you'll have to tell Ladies from Tigers
- A new twist is being added.
  - **Three** doors!
  - One lady, **TWO** tigers
  - At most one of the signs is true

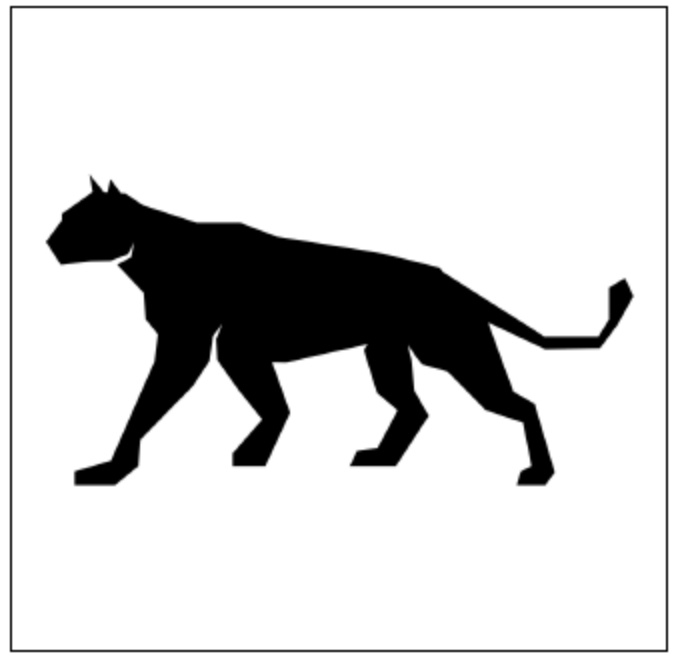
The Lady and the Tiger
Q2

Room I	Room II	Room III
A tiger is in this room.	A lady is in this room.	A tiger is in room II.

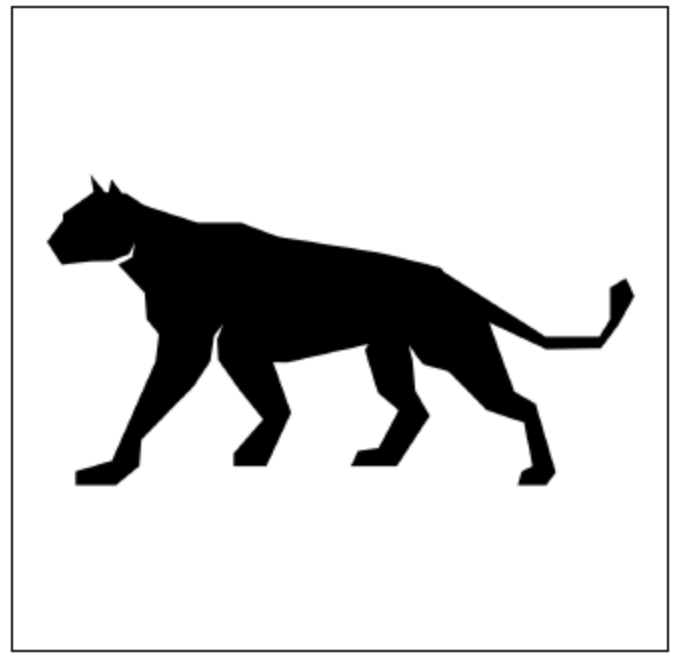
The Lady and the Tiger
Q2

Room I

Room II



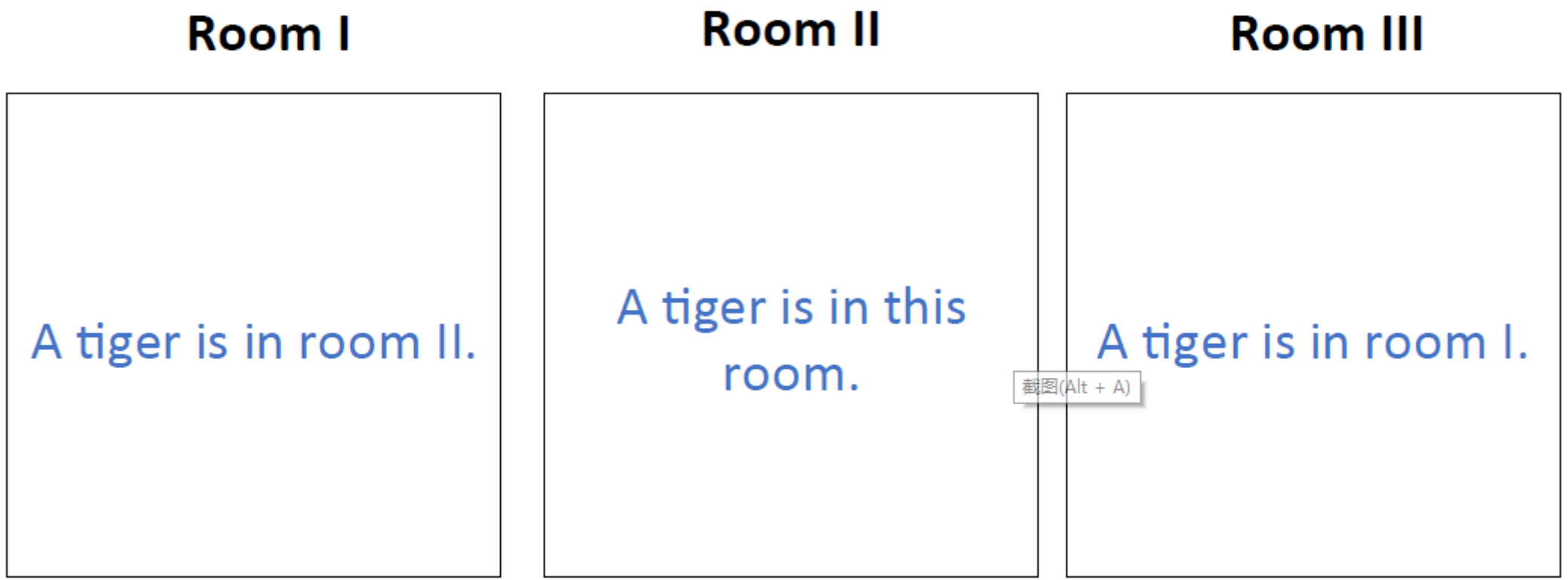
Room III



The Lady and the Tiger

- Once again, you'll have to tell Ladies from Tigers
- A new twist is being added.
  - Three doors!
  - One lady, TWO tigers
  - The sign on the door of the room with the lady is true. At least one of the other two signs is false!

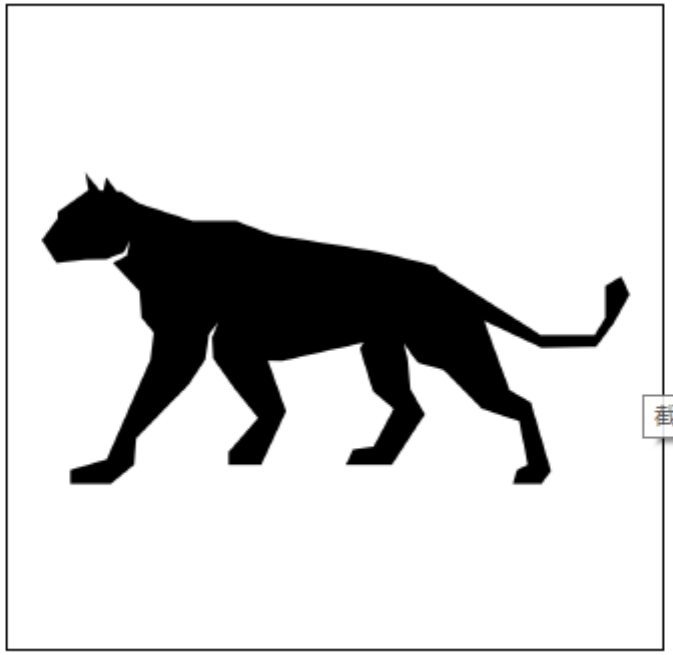
The Lady and the Tiger
Q3



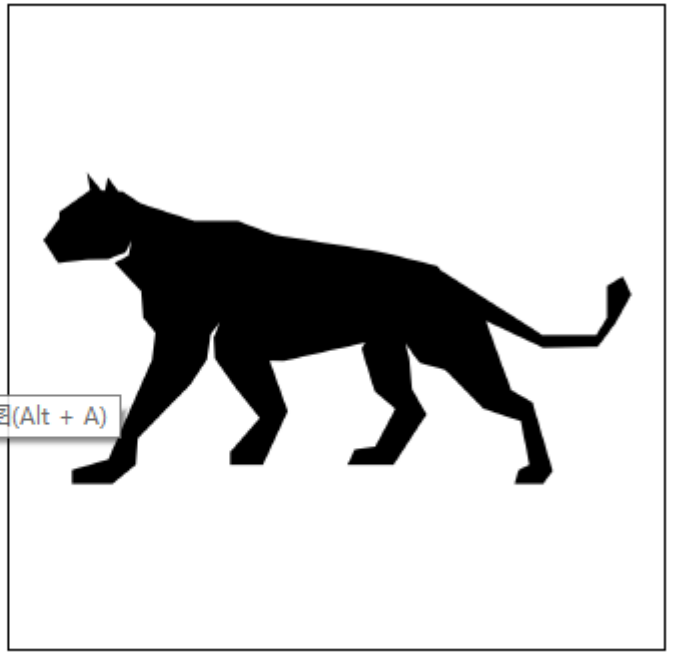
The Lady and the Tiger
Q3

Room I

Room II



Room III



截图(Alt + A)

The Lady and the Tiger

- Only one room contains a lady. Every other room has a tiger, or is empty.
- The sign of the door with the lady is true. The signs of all rooms with tigers are false. Empty room's signs can be true or false.
- This problem would be unsolvable, however, if you knew if Room VIII was empty or not, you'd be able to figure out which room had the lady.

Room I

The lady is in an odd numbered room.

Room II

This room is empty.

Room III

Either Sign V is right or Sign VII is wrong.

Room IV

Sign I is wrong.

Room V

Either Sign II or Sign IV is right.

Room VI

Sign III is wrong.

Room VII

The lady is not in Room I

Room VIII

This room contains a tiger and room IX is empty.

Room IX

This room contains a tiger and VI is wrong.

（二）

等价公式

- 矛盾律：A /\ !A = false
- 排中律： A \/ !A = true
- 零律：! A /\ false = false, A \/ true = true
- 同一律：A \/ false = A, A /\ true = A
- 双重否定律：!!A = A
- 等幂律：A /\ A = A, A \/ A = A

等价公式

- 分配律：A /\ (B \/ C) = (A /\ B) \/ (A /\ C)
- A \/ (B /\ C) = (A \/ B) /\ (A \/ C)

- 结合律：A /\ (B /\ C) = (A /\ B) /\ C
- A \/ (B \/ C) = (A \/ B) \/ C

- 交换律：A \/ B = B \/ A,　　A /\ B = B /\ A

- 德摩根律：!(A \/ B) = !A /\ !B,　　!(A /\ B) = !A \/ !B

- 吸收律：A \/ (A /\ B) = A,　　A /\ (A \/ B) = A

等价公式

- 蕴含等值律：A -> B = !A \/ B
- 等价等值律：A <-> B = (A -> B) /\ (B -> A)
- 假言律：A -> B = !B -> !A
- 等价否定律：A <-> B = !A <-> !B
- 附加律：A => A \/ B
- 化简律：A /\ B => A

课堂练习

- 证明：(A->B) /\ (B -> C) => (A -> C) （假言三段论）
- 化简：(A \/ C) /\ ((A /\ D) \/ (!A /\ D)) \/ (A /\ C) \/ C = ?
- 化简：A \/ (!A /\ B) \/ (!A /\ !B /\ C) \/ (!A /\ !B /\ !C /\ D) \/ (!A/\ !B /\ !C /\ !D /\ E) = ?

合取范式 (CNF)和析取范式 (DNF)

- 合取范式

  具有如$\Lambda(\mathrm{V}\,p)$形式的布尔逻辑公式

- 析取范式

  具有如$\mathrm{V}(\Lambda\,p)$形式的布尔逻辑公式

合取范式 (CNF)和析取范式 (DNF)

原公式：(a | b) & (c | (b & d))

合取范式CNF: (a | b) & (c | b) & (c | d))

析取范式DNF: (a & c) | (a & b & d) | (b & c) | (b & d)

合取范式 (CNF)和析取范式 (DNF)

- a & b & c 是CNF吗？是DNF吗？

合取范式 (CNF)和析取范式 (DNF)

- a & b & c 是CNF吗？是DNF吗？

- a | b | c 是CNF吗？是DNF吗？

合取范式 (CNF)和析取范式 (DNF)

- a & b & c 是CNF吗？是DNF吗？
- a | b | c 是CNF吗？是DNF吗？
- (a & b) | c 是CNF吗？是DNF吗？

合取范式 (CNF)和析取范式 (DNF)

- a & b & c 是CNF吗？是DNF吗？
- a | b | c 是CNF吗？是DNF吗？
- (a & b) | c 是CNF吗？是DNF吗？
- (a | b) & (b | (c & d)) 是CNF吗？是DNF吗？

思考题

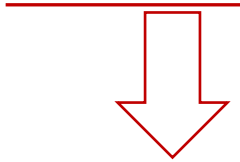
给定任意一个布尔逻辑公式，如何转成它对应的合取（析取）范式?

合取范式 (CNF)和析取范式 (DNF)

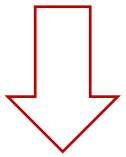
- (a | b) & (b | (c & d))

合取范式 (CNF)和析取范式 (DNF)

- (a | b) & (b | (c & d))



(b | c) & (b | d)



(a | b) & (b | c) & (b | d)

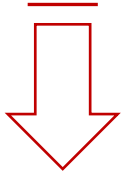
合取范式

合取范式 (CNF)和析取范式 (DNF)

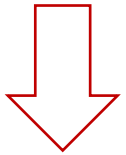
- (a | b) & (b | (c & d))

合取范式 (CNF)和析取范式 (DNF)

- (a | b) & (b | (c & d))



(a & (b | (c & d))) | (b & (b | (c & d)))



(a & b) | (a & c & d) | b | (b & c & d)

析取范式

课堂练习

求下列公式的合取范式和析取范式

- (A -> !B) <-> C
- (A <-> B) -> (B /\ C)

析取范式 (DNF)和解的关系

(a & b) | (a & c & d) | b | (b & c & d)

{a=1, b=1, c=X, d=X}

析取范式 (DNF)和解的关系

(a & b) | (a & c & d) | b | (b & c & d)

{a=1, b=1, c=X, d=X}

{a=1, b=X, c=1, d=1}

析取范式 (DNF)和解的关系

(a | b) & (b | (c & d))

(a & b) | (a & c & d) | b | (b & c & d)

长度指数级增长!

合取范式 (CNF)和解的关系

(a | b) & (b | c) & (b | d)

合取范式 (CNF)和解的关系

(a | b) & (b | c) & (b | d)

主流的SAT求解器都是基于CNF输入。

合取范式 (CNF)和解的关系

(a | b) & (b | (c & d))

(a | b) & (b | c) & (b | d)

合取范式 (CNF)和解的关系

(a | b) & (b | (c & d))

(a | b) & (b | c) & (b | d)

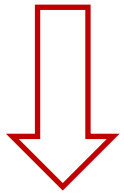
长度指数级增长!

Tseitin 转换(1968)

(a | b) & (b | (c & d))

Tseitin 转换(1968)

(a | b) & (b | (c & d))



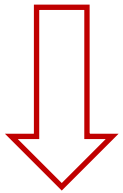
x1 & x2 &

x1⇔(a | b) &

x2⇔(b | (c & d))

Tseitin 转换(1968)

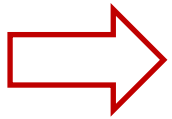
(a | b) & (b | (c & d))



x1 & x2 &

x1⇔(a | b) &

x2⇔(b | (c & d))



x1 & x2 &

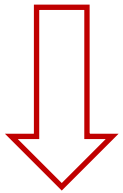
x1⇔(a | b) &

x2⇔(b | x3) &

x3 ⇔c & d

Tseitin 转换(1968)

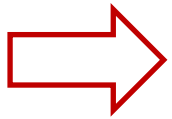
(a | b) & (b | (c & d))



x1 & x2 &

x1⇔(a | b) &

x2⇔(b | (c & d))

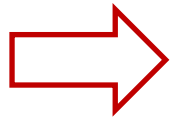


x1 & x2 &

x1⇔(a | b) &

x2⇔(b | x3) &

x3 ⇔c & d



x1 & x2 &

(!x1 | a | b) &

(!a | x1) &

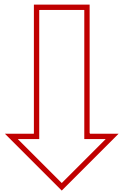
(!b | x1) &

x2⇔(b | x3) &

x3 ⇔c & d

Tseitin 转换(1968)

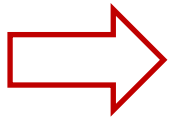
(a | b) & (b | (c & d))



x1 & x2 &

x1⇔(a | b) &

x2⇔(b | (c & d))

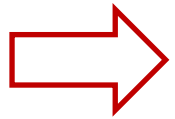


x1 & x2 &

x1⇔(a | b) &

x2⇔(b | x3) &

x3 ⇔c & d



x1 & x2 &

(!x1 | a | b) &

(!a | x1) &

(!b | x1) &

(!x2 | b | x3) &

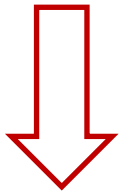
(!b | x2) &

(!x3 | x2) &

x3 ⇔c & d

Tseitin 转换(1968)

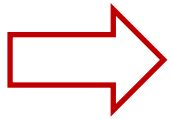
(a | b) & (b | (c & d))



x1 & x2 &

x1⇔(a | b) &

x2⇔(b | (c & d))

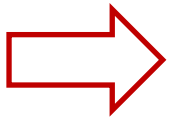


x1 & x2 &

x1⇔(a | b) &

x2⇔(b | x3) &

x3 ⇔c & d



x1 & x2 &

(!x1 | a | b) &

(!a | x1) &

(!b | x1) &

(!x2 | b | x3) &

(!b | x2) &

(!x3 | x2) &

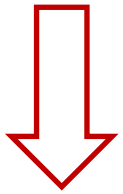
(x3 | !c | !d) &

(!x3 | c) &

(!x3 | d)

Tseitin 转换(1968)

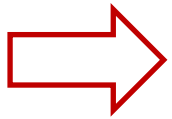
(a | b) & (b | (c & d))



x1 & x2 &

x1⇔(a | b) &

x2⇔(b | (c & d))

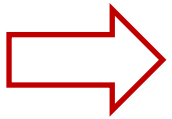


x1 & x2 &

x1⇔(a | b) &

x2⇔(b | x3) &

x3 ⇔c & d



等可满足

x1 & x2 &

(!x1 | a | b) &

(!a | x1) &

(!b | x1) &

(!x2 | b | x3) &

(!b | x2) &

(!x3 | x2) &

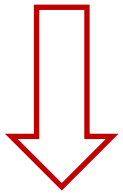
(x3 | !c | !d) &

(!x3 | c) &

(!x3 | d)

Tseitin 转换(1968)

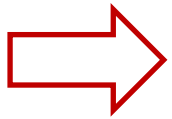
(a | b) & (b | (c & d))



x1 & x2 &

x1⇔(a | b) &

x2⇔(b | (c & d))

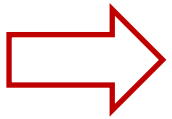


x1 & x2 &

x1⇔(a | b) &

x2⇔(b | x3) &

x3 ⇔c & d



x1 & x2 &

(!x1 | a | b) &

(!a | x1) &

(!b | x1) &

(!x2 | b | x3) &

(!b | x2) &

(!x3 | x2) &

(x3 | !c | !d) &

(!x3 | c) &

(!x3 | d)

课堂练习

用Tseitin求下列公式对应的CNF （提示：把->和<->先消去）

- （A -> !B） <-> C
- （A <-> B） -> (B /\ C)

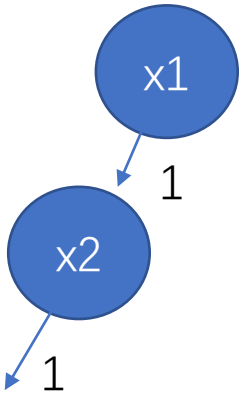
（三）

DPLL算法

x1 &
x2 &
(!x1 | a | b) &
(!a | x1) &
(!b | x1) &
(!x2 | b | x3) &
(!b | x2) &
(!x3 | x2) &
(x3 | !c | !d) &
(!x3 | c) &
(!x3 | d)

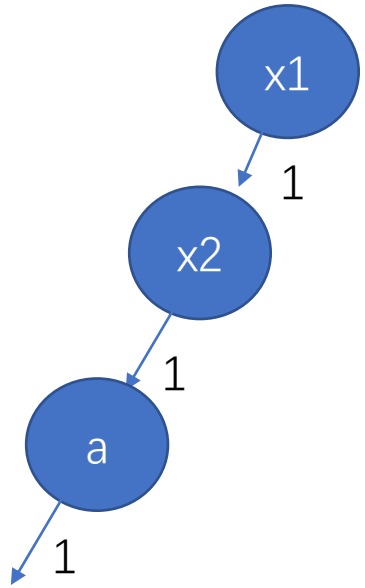
DPLL算法

x1 &
x2 &
(!x1 | a | b) &
(!a | x1) &
(!b | x1) &
(!x2 | b | x3) &
(!b | x2) &
(!x3 | x2) &
(x3 | !c | !d) &
(!x3 | c) &
(!x3 | d)



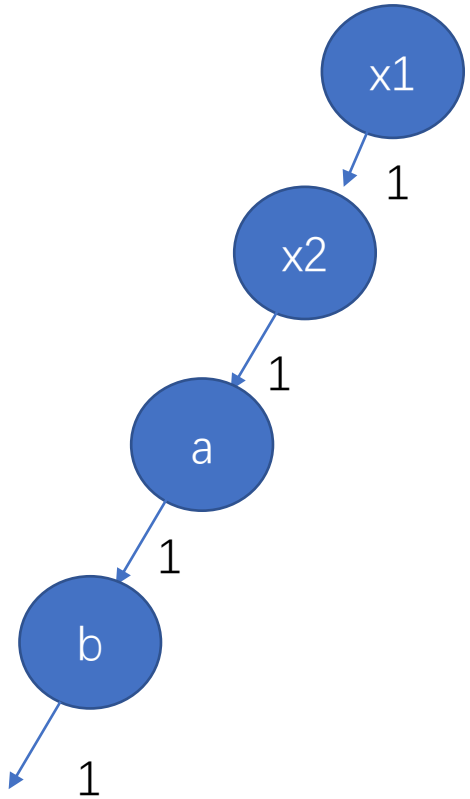
DPLL算法

x1 &
x2 &
(!x1 | a | b) &
(!a | x1) &
(!b | x1) &
(!x2 | b | x3) &
(!b | x2) &
(!x3 | x2) &
(x3 | !c | !d) &
(!x3 | c) &
(!x3 | d)



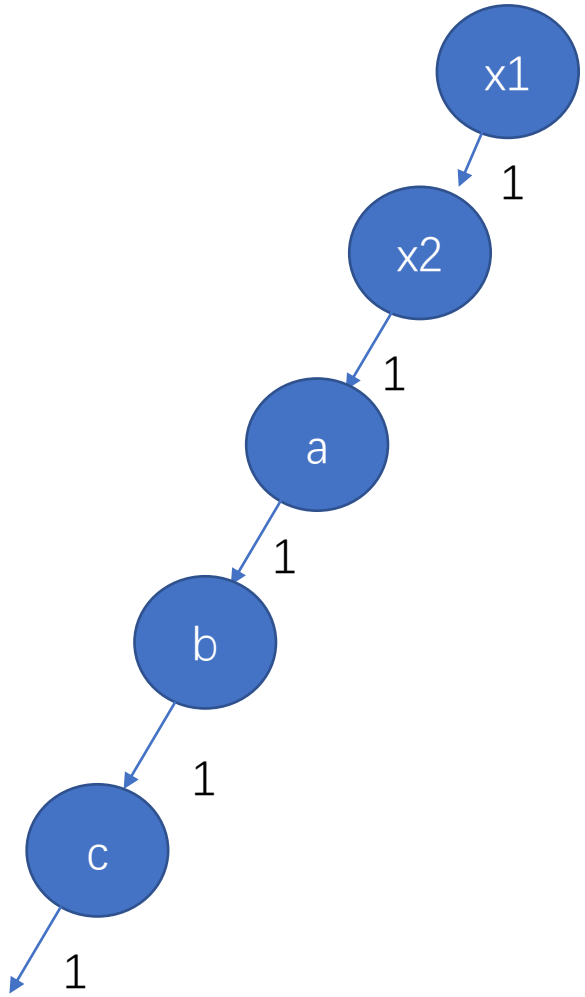
DPLL算法

x1 &
x2 &
(!x1 | a | b) &
(!a | x1) &
(!b | x1) &
(!x2 | b | x3) &
(!b | x2) &
(!x3 | x2) &
(x3 | !c | !d) &
(!x3 | c) &
(!x3 | d)



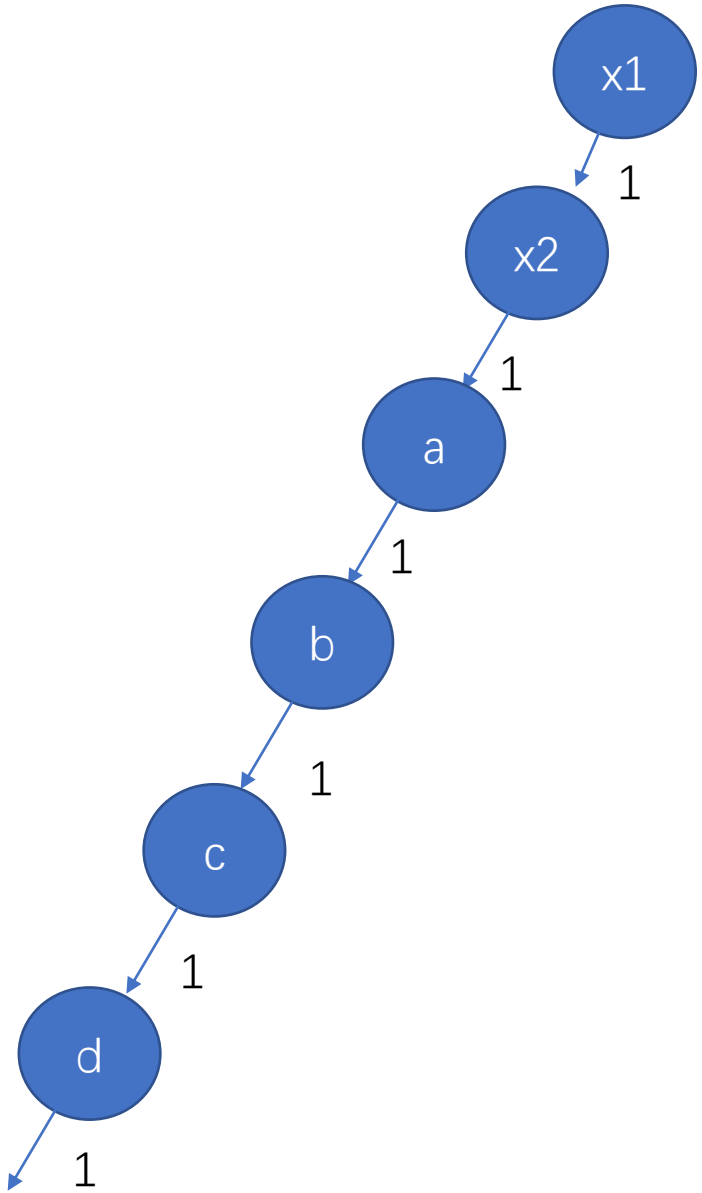
DPLL算法

x1 &
x2 &
(!x1 | a | b) &
(!a | x1) &
(!b | x1) &
(!x2 | b | x3) &
(!b | x2) &
(!x3 | x2) &
(x3 | !c | !d) &
(!x3 | c) &
(!x3 | d)



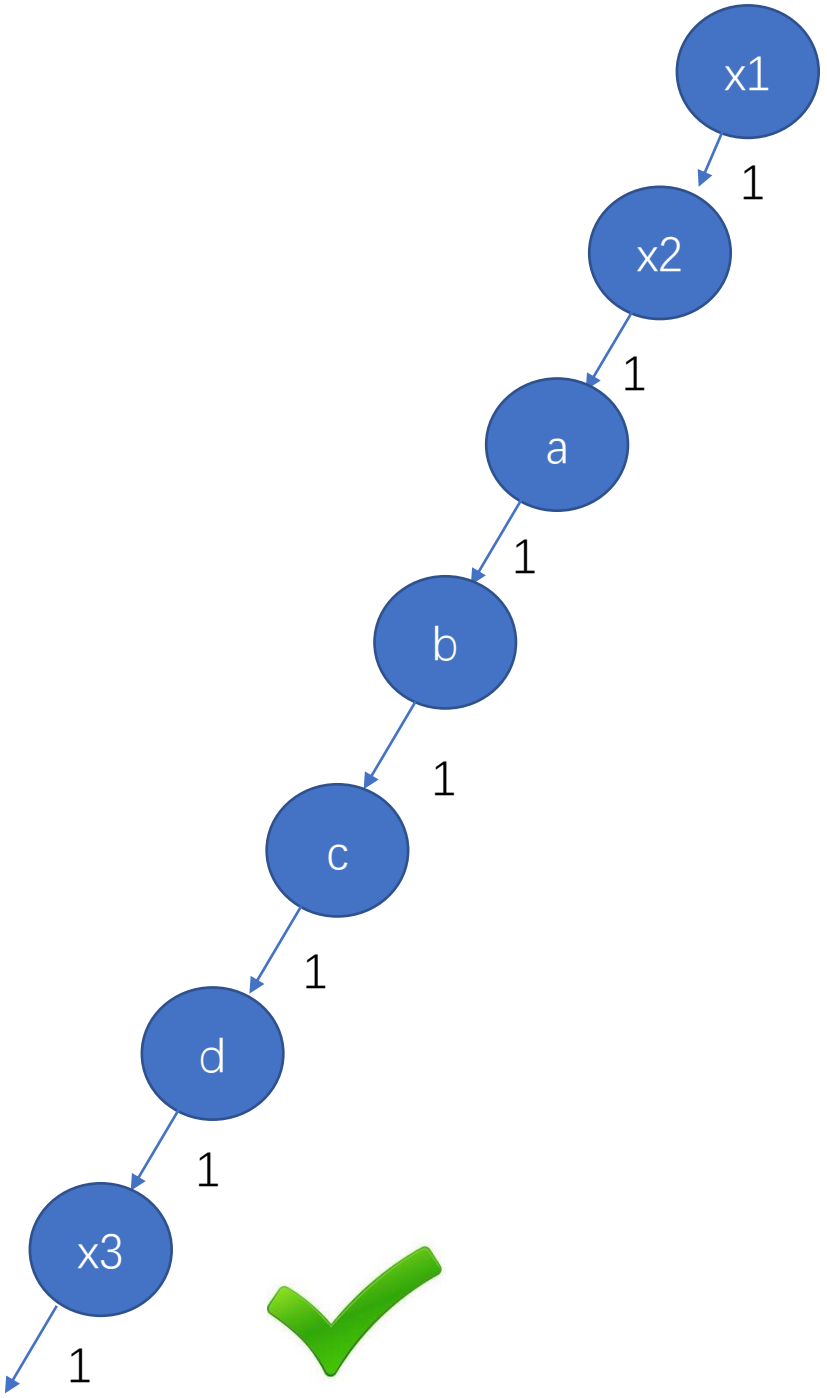
DPLL算法

x1 &
x2 &
(!x1 | a | b) &
(!a | x1) &
(!b | x1) &
(!x2 | b | x3) &
(!b | x2) &
(!x3 | x2) &
(x3 | !c | !d) &
(!x3 | c) &
(!x3 | d)



DPLL算法

x1 &
x2 &
(!x1 | a | b) &
(!a | x1) &
(!b | x1) &
(!x2 | b | x3) &
(!b | x2) &
(!x3 | x2) &
(x3 | !c | !d) &
(!x3 | c) &
(!x3 | d)

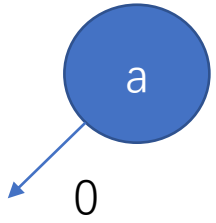


DPLL算法

(!a | b | c) &
(a | c | d) &
(a | c |!d) &
(a | !c | d) &
(a | !c | !d) &
(!b | !c | d) &
(!a | b | !c) &
(!a | !b | c)

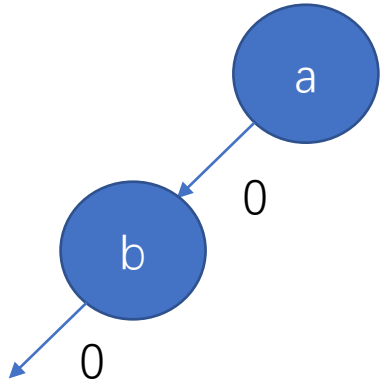
DPLL算法

(!a | b | c) &
(a | c | d) &
(a | c |!d) &
(a | !c | d) &
(a | !c | !d) &
(!b | !c | d) &
(!a | b | !c) &
(!a | !b | c)



DPLL算法

(!a | b | c) &
(a | c | d) &
(a | c |!d) &
(a | !c | d) &
(a | !c | !d) &
(!b | !c | d) &
(!a | b | !c) &
(!a | !b | c)



DPLL算法

(!a | b | c) &

(a | c | d) &

(a | c |!d) &

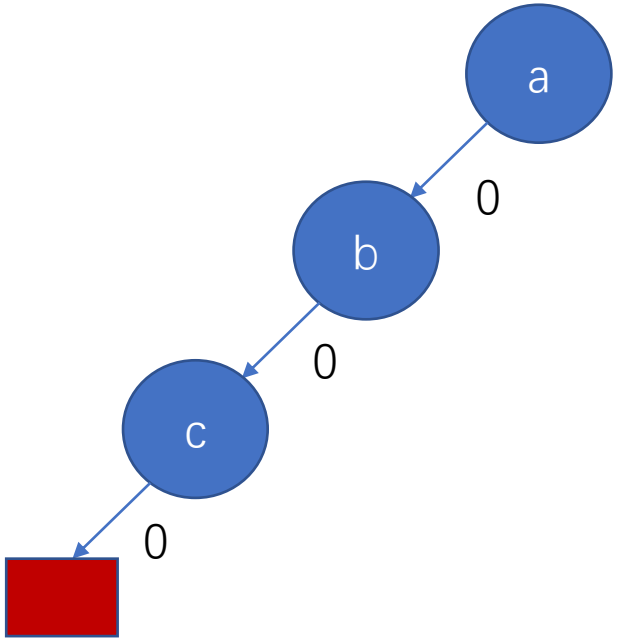
(a | !c | d) &

(a | !c | !d) &

(!b | !c | d) &

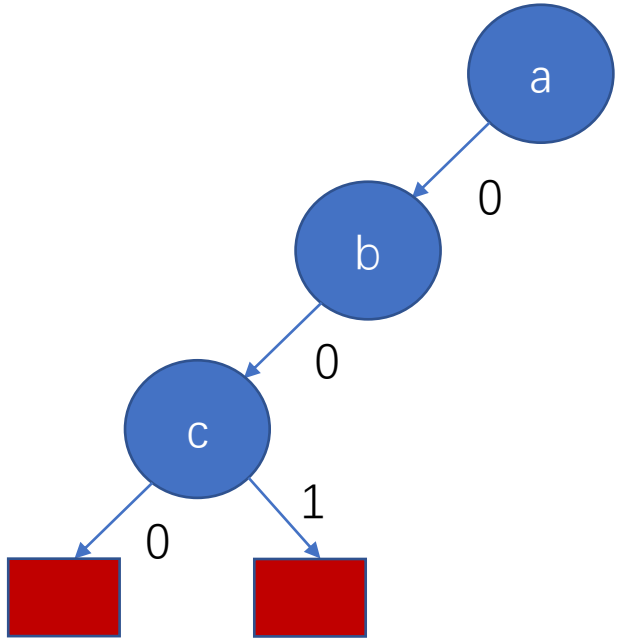
(!a | b | !c) &

(!a | !b | c)



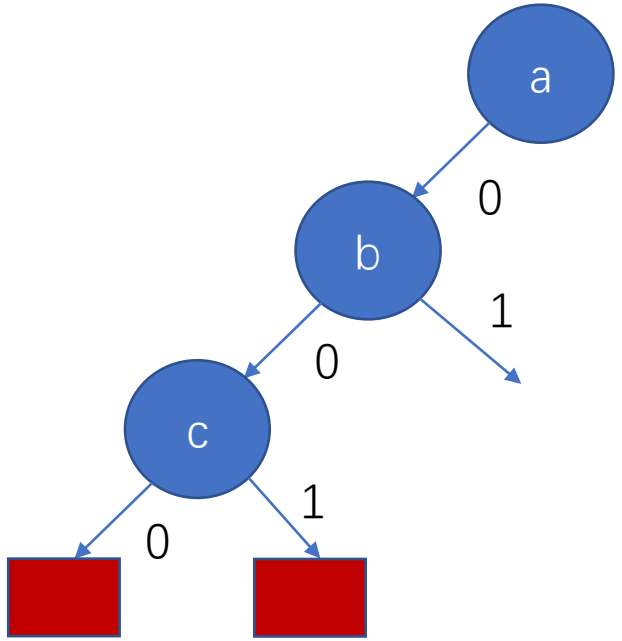
DPLL算法

(!a | b | c) &
(a | c | d) &
(a | c |!d) &
(a | !c | d) &
(a | !c | !d) &
(!b | !c | d) &
(!a | b | !c) &
(!a | !b | c)



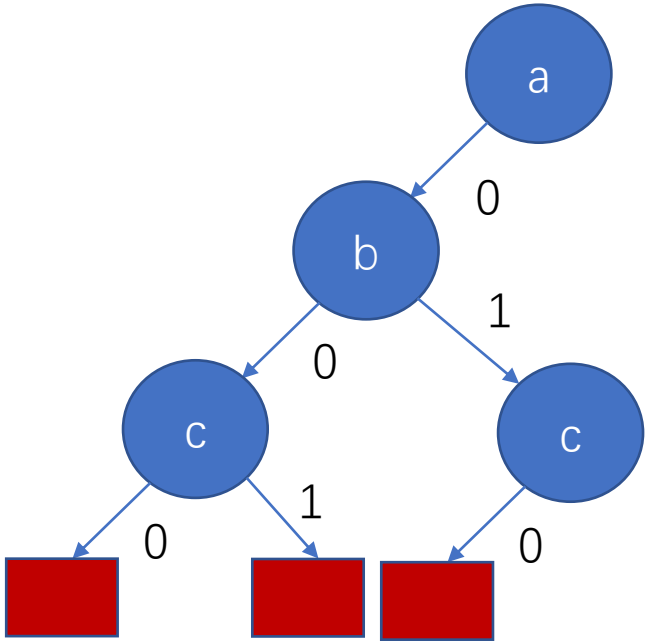
DPLL算法

(!a | b | c) &
(a | c | d) &
(a | c |!d) &
(a | !c | d) &
(a | !c | !d) &
(!b | !c | d) &
(!a | b | !c) &
(!a | !b | c)



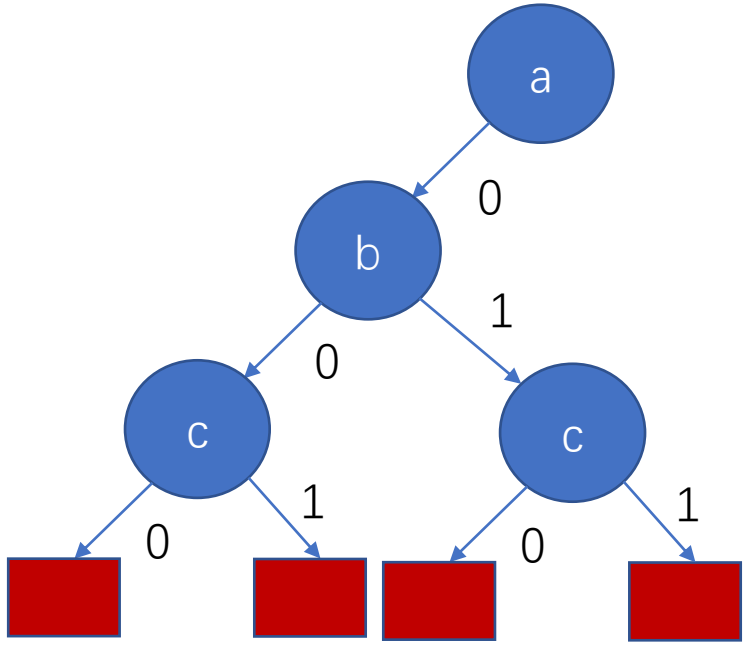
DPLL算法

(!a | b | c) &
(a | c | d) &
(a | c |!d) &
(a | !c | d) &
(a | !c | !d) &
(!b | !c | d) &
(!a | b | !c) &
(!a | !b | c)



DPLL算法

(!a | b | c) &
(a | c | d) &
(a | c |!d) &
(a | !c | d) &
(a | !c | !d) &
(!b | !c | d) &
(!a | b | !c) &
(!a | !b | c)



DPLL算法

(!a | b | c) &

(a | c | d) &

(a | c |!d) &

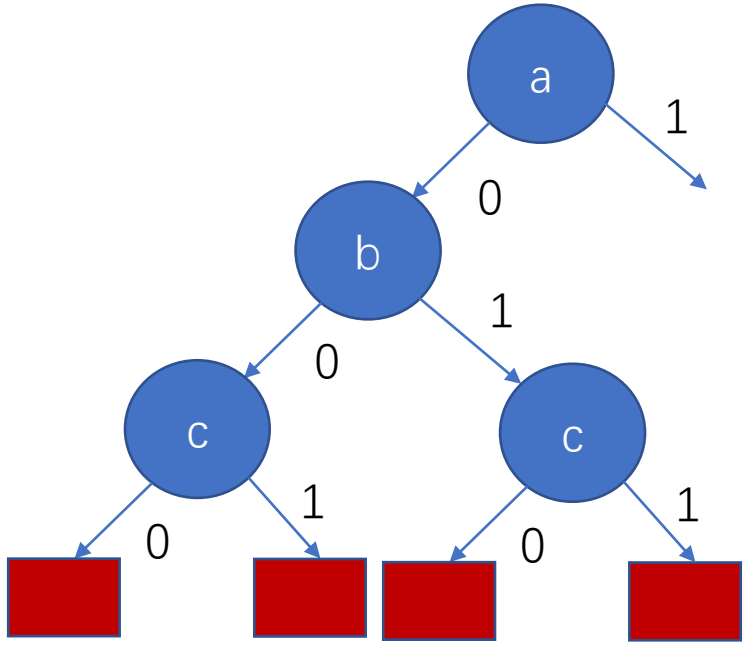
(a | !c | d) &

(a | !c | !d) &

(!b | !c | d) &

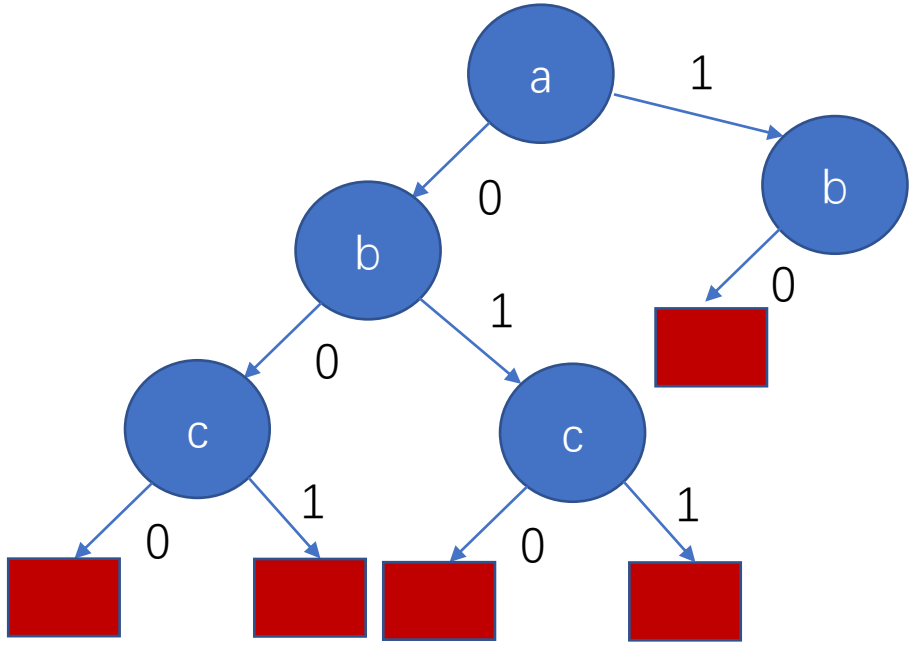
(!a | b | !c) &

(!a | !b | c)



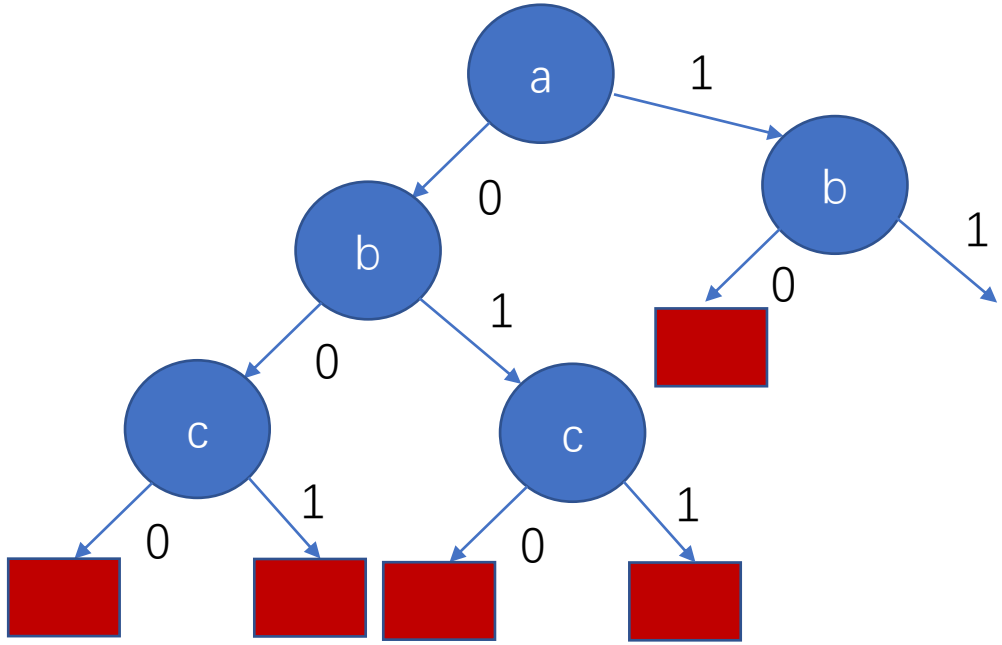
DPLL算法

(!a | b | c) &
(a | c | d) &
(a | c |!d) &
(a | !c | d) &
(a | !c | !d) &
(!b | !c | d) &
(!a | b | !c) &
(!a | !b | c)



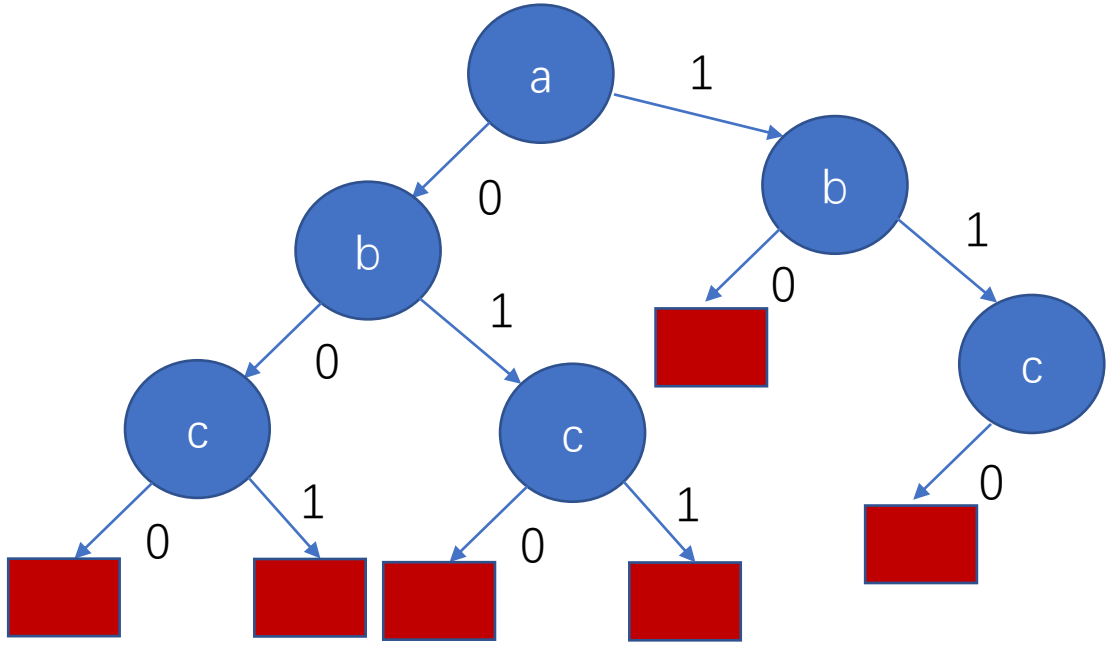
DPLL算法

(!a | b | c) &
(a | c | d) &
(a | c |!d) &
(a | !c | d) &
(a | !c | !d) &
(!b | !c | d) &
(!a | b | !c) &
(!a | !b | c)



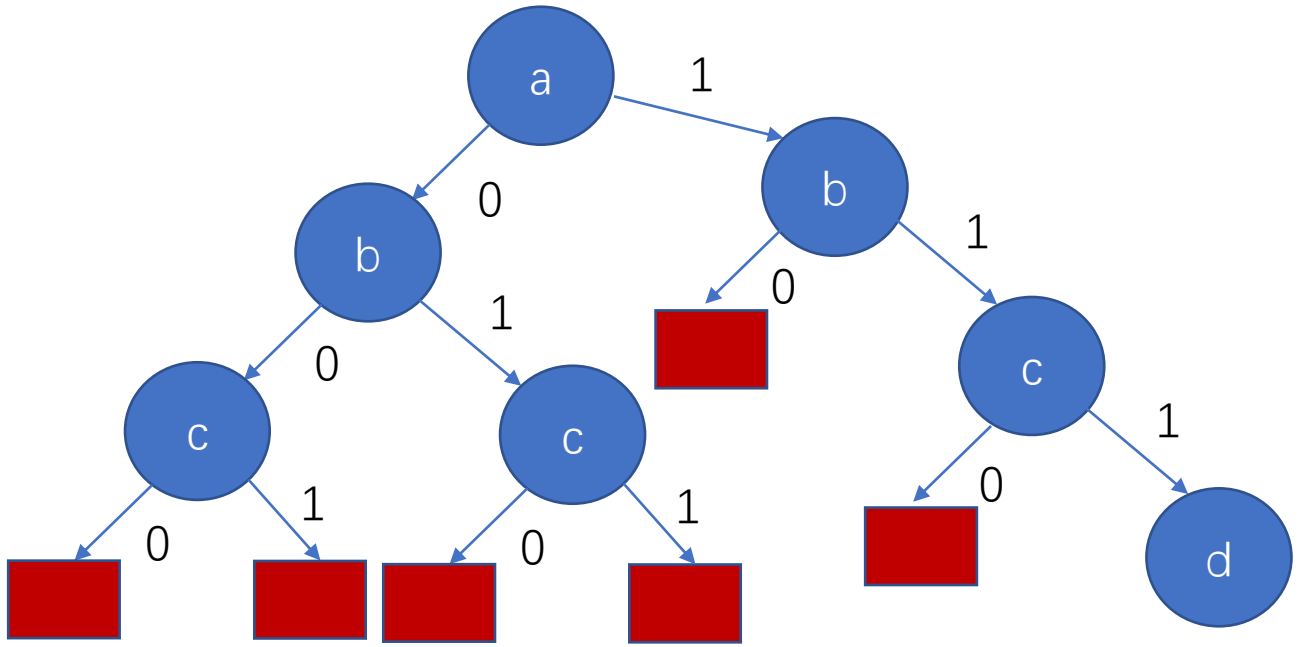
DPLL算法

(!a | b | c) &
(a | c | d) &
(a | c |!d) &
(a | !c | d) &
(a | !c | !d) &
(!b | !c | d) &
(!a | b | !c) &
(!a | !b | c)



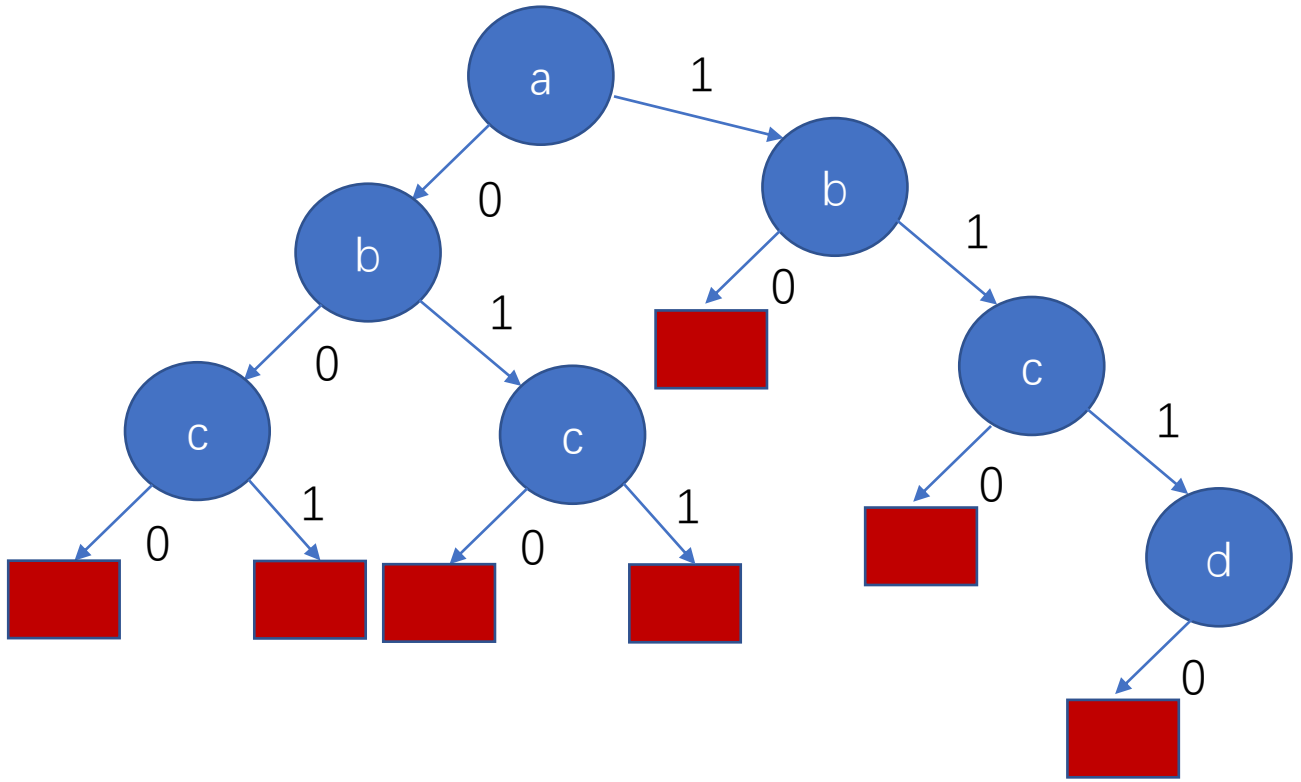
DPLL算法

(!a | b | c) &
(a | c | d) &
(a | c |!d) &
(a | !c | d) &
(a | !c | !d) &
(!b | !c | d) &
(!a | b | !c) &
(!a | !b | c)



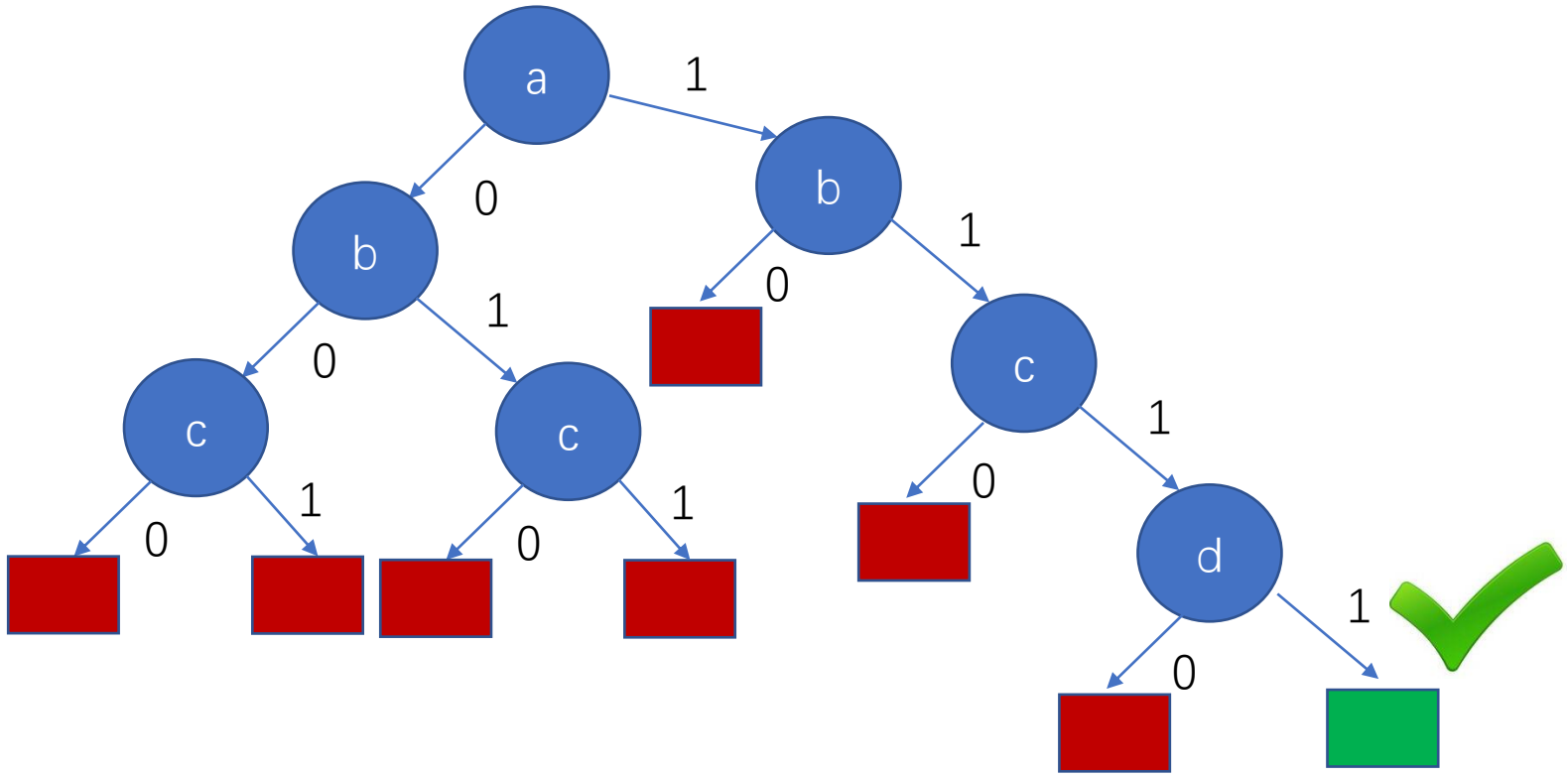
DPLL算法

(!a | b | c) &
(a | c | d) &
(a | c |!d) &
(a | !c | d) &
(a | !c | !d) &
(!b | !c | d) &
(!a | b | !c) &
(!a | !b | c)



DPLL算法

(!a | b | c) &
(a | c | d) &
(a | c |!d) &
(a | !c | d) &
(a | !c | !d) &
(!b | !c | d) &
(!a | b | !c) &
(!a | !b | c)



课堂练习

使用DPLL算法求下面公式的解

- (A \/ B) /\ (B \/ !C \/ D) /\ (!A \/ !B) /\ (!A \/ !C \/ !D) /\ A
- (A /\ B) \/ (!B /\ !C) \/ (A /\ !C /\ D) （提示：先用Tsitin转换）

SAT (Boolean SATisfiability Problem)

给定一个布尔逻辑公式，判定其是否存在解的过程。

SAT是第一个被证明的NP完全问题。（1970）

很多问题都可以转化为SAT问题解决，比如验证问题。

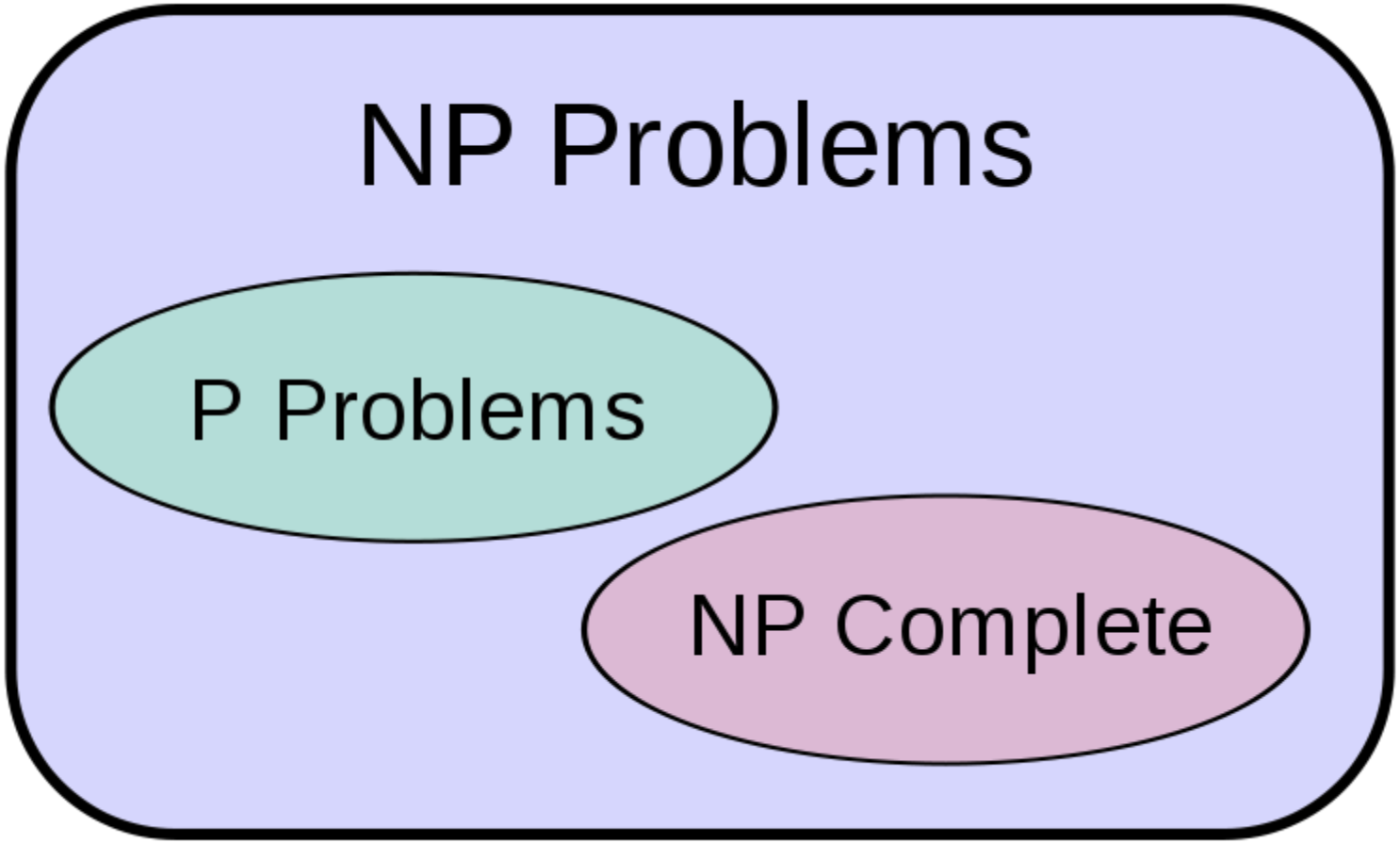
P = NP?

数学界7大未解问题之一：100万美金的奖励。

P：给定一个问题和解，判定解是否为该问题的真实解。

NP：给定一个问题，寻找该问题的一个真实解。

P = NP?



思考题

有没有更高效的SAT求解算法?

DIMACS: 基于CNF的SAT求解器输入

(!a | b | c) &
(a | c | d) &
(a | c |!d) &
(a | !c | d) &
(a | !c | !d) &
(!b | !c | d) &
(!a | b | !c) &
(!a | !b | c)

```
p cnf 4 8
-1 2 3 0
1 3 4 0
1 3 -4 0
1 -3 4 0
1 -3 -4 0
-2 -3 4 0
-1 2 -3 0
-1 -2 3 0
c a=1, b=2, c=3, d=4
```

文件头p cnf，变量和项个数

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文件头p cnf，变量和项个数

注释

国际SAT年度竞赛：http://www.satcompetition.org/

课程小结—布尔逻辑

- 布尔逻辑基本概念介绍
- 布尔逻辑公式的合取范式(CNF)和析取范式(DNF)
- 布尔公式求解（SAT）DPLL算法简介