Logic in AI
Chapter 7

Mausam

(Based on slides of Dan Weld, Stuart Russell, Subbarao Kambhampati, Dieter Fox, Henry Kautz…)

Logic: another thing that penguins aren't very good at.

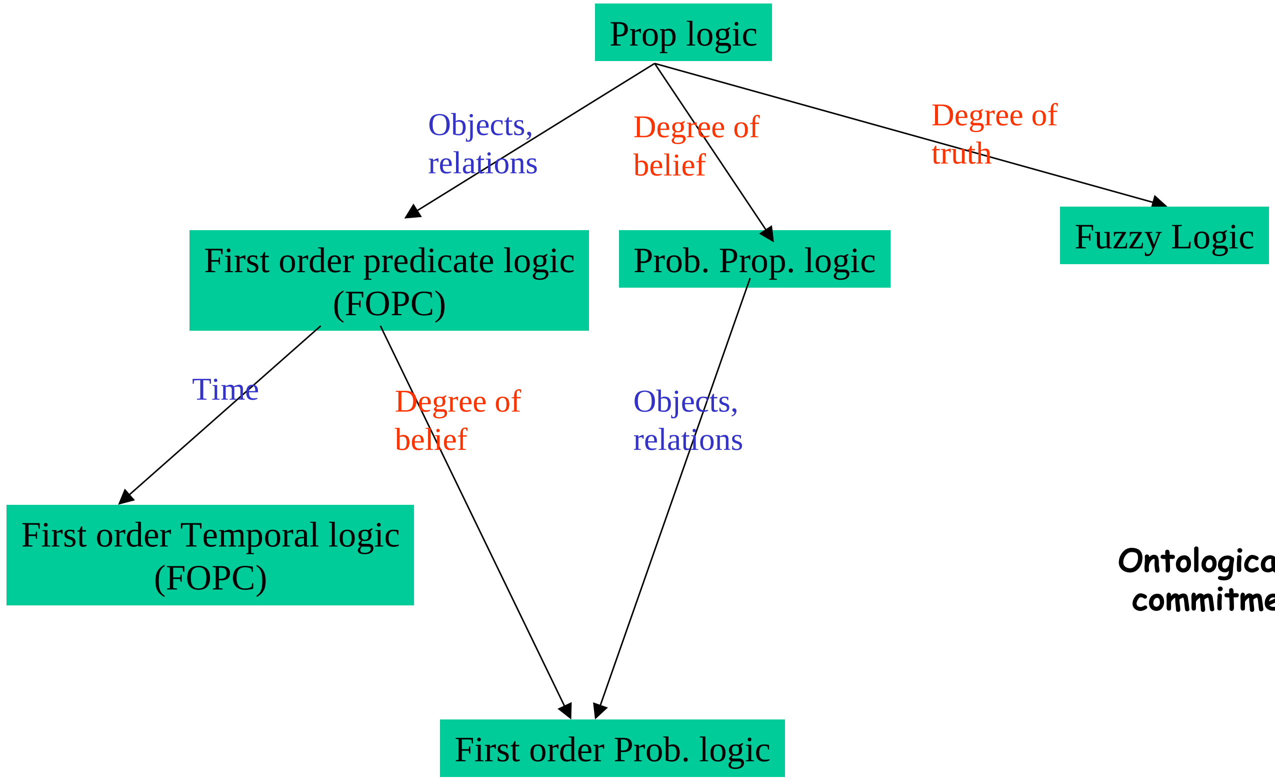
Knowledge Representation

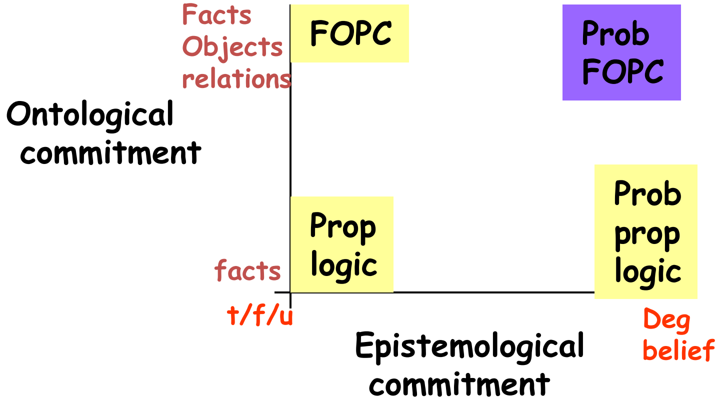
- *represent knowledge about the world in a manner that facilitates inferencing (i.e. drawing conclusions) from knowledge.*

- Example: Arithmetic logic
  - x >= 5

- In AI: typically based on
  - Logic
  - Probability
  - Logic and Probability

Common KR Languages





KR Languages

- Propositional Logic
- Predicate Calculus
- Frame Systems
- Rules with Certainty Factors
- Bayesian Belief Networks
- Influence Diagrams
- Ontologies
- Semantic Networks
- Concept Description Languages
- Non-monotonic Logic

Basic Idea of Logic

- By starting with true assumptions, you can deduce true conclusions.

Truth

•Francis Bacon (1561-1626)

No pleasure is comparable to the standing upon the vantage-ground of truth.

•Thomas Henry Huxley (1825-1895)

Irrationally held truths may be more harmful than reasoned errors.

•John Keats (1795-1821)

Beauty is truth, truth beauty; that is all ye know on earth, and all ye need to know.

•Blaise Pascal (1623-1662)

We know the truth, not only by the reason, but also by the heart.

•François Rabelais (c. 1490-1553)

Speak the truth and shame the Devil.

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Components of KR

- Syntax: defines the sentences in the language
- Semantics: defines the "meaning" to sentences
- Inference Procedure
  - Algorithm
  - Sound?
  - Complete?
  - Complexity
- Knowledge Base

Knowledge bases

- Knowledge base = set of sentences in a formal language

- Declarative approach to building an agent (or other system):
  - `Tell` it what it needs to know

- Then it can `Ask` itself what to do - answers should follow from the KB

- Agents can be viewed at the knowledge level
  i.e., what they know, regardless of how implemented

- Or at the implementation level
  i.e., data structures in KB and algorithms that manipulate them

Propositional Logic

- Syntax
  - Atomic sentences: P, Q, …
  - Connectives: $\wedge$, $\vee$, $\neg$, $\rightarrow$
- Semantics
  - Truth Tables
- Inference
  - Modus Ponens
  - Resolution
  - DPLL
  - GSAT

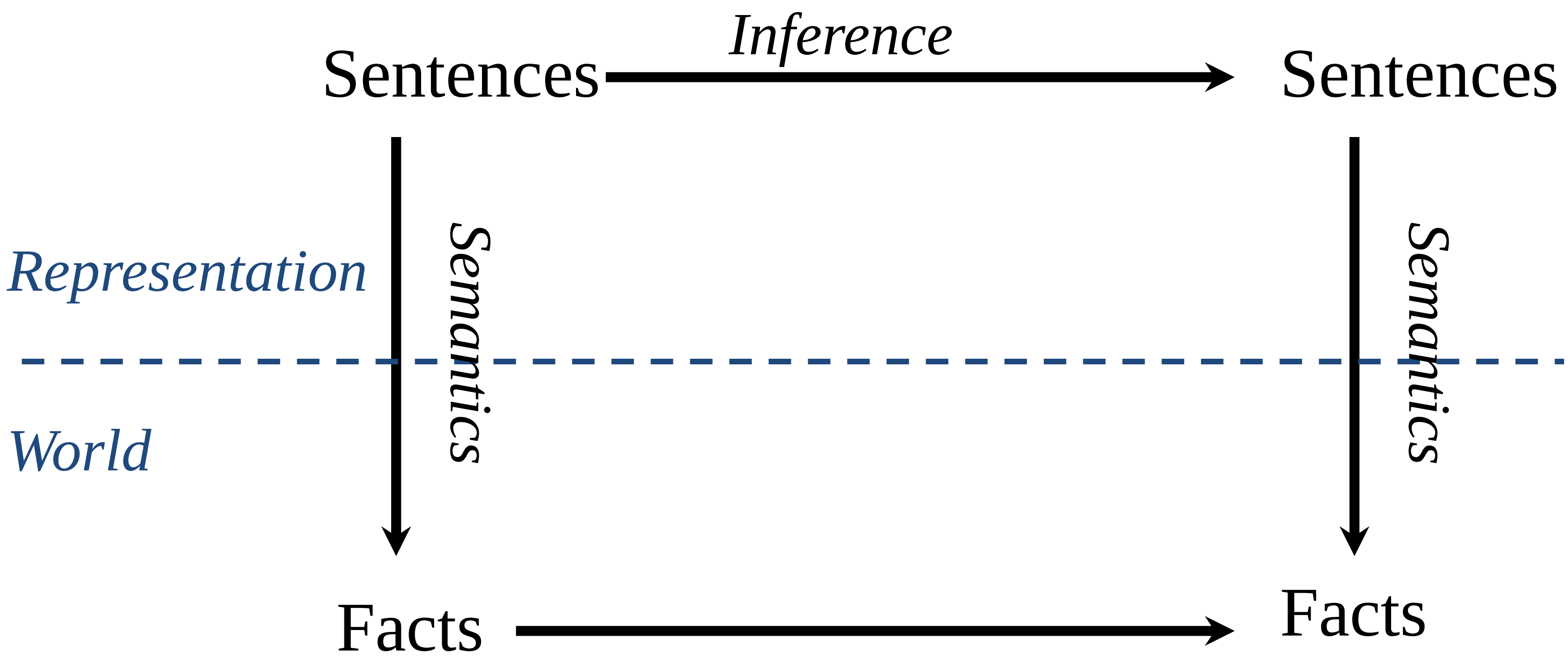
Propositional Logic: Syntax

- Atoms
  - P, Q, R, …
- Literals
  - P, $\neg$P
- Sentences
  - Any literal is a sentence
  - If S is a sentence
    - Then (S $\wedge$ S) is a sentence
    - Then (S $\vee$ S) is a sentence
- Conveniences

P → Q same as $\neg$P $\vee$ Q

Semantics

- ***Syntax***: which arrangements of symbols are *legal*
  - (Def "sentences")
- ***Semantics***: what the symbols *mean* in the world
  - (Mapping between symbols and worlds)



Propositional Logic: **SEMANTICS**

- “Interpretation” (or “possible world”)
  - Assignment to each variable either T or F
  - Assignment of T or F to each connective via defns

		Q	
		T	F
P	T		
	F		

$P \wedge Q$

		Q	
		T	F
P	T		
	F		

$P \vee Q$

Propositional Logic: **SEMANTICS**

- "Interpretation" (or "possible world")
  - Assignment to each variable either T or F
  - Assignment of T or F to each connective via defns

P \ Q	T	F
T	T	F
F	F	F

$P \land Q$

P \ Q	T	F
T		
F		

$P \lor Q$

Propositional Logic: **SEMANTICS**

- "Interpretation" (or "possible world")
  - Assignment to each variable either T or F
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$P \wedge Q$

P \ Q	T	F
T	T	F
F	F	F

$P \vee Q$

P \ Q	T	F
T	T	T
F	T	F

Satisfiability, Validity, & Entailment

- S is **satisfiable** if it is true in ***some*** world
- S is **unsatisfiable** if it is false ***all*** worlds
- S is **valid** if it is true in ***all*** worlds
- S1 **entails** S2 if ***wherever*** S1 is true S2 is also true

Examples

$P \rightarrow Q$

Examples

$P \rightarrow Q$

$R \rightarrow \neg R$

Examples

$P \rightarrow Q$

$R \rightarrow \neg R$

$S \wedge (W \wedge \neg S)$

Examples

$P \rightarrow Q$

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$T \vee \neg T$

Examples

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$X \rightarrow X$

Notation

$\Rightarrow$

$\supset$

$\rightarrow$

$\vdash$

$\models$

Notation

$\Rightarrow$

$\supset$ } **Implication** (syntactic symbol)

$\rightarrow$

$\vdash$

$\models$

Notation

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$\vdash$ **Proves:** S1 $|-_{ie}$ S2 if `ie' algorithm says `S2' from S1

$\models$ **Entails:** S1 |= S2 if wherever S1 is true S2 is also true

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- **Sound**
- **Complete**
- *(all truth & nothing but the truth)*

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$\Rightarrow$
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- **Sound** $\vdash \rightarrow \models$
- **Complete** $\models \rightarrow \vdash$
- *(all truth & nothing but the truth)*

Reasoning Tasks

- Model finding

  KB = background knowledge

  S = description of problem

  Show (KB $\wedge$ S) is satisfiable

  A kind of constraint satisfaction

- Deduction

  S = question

  Prove that KB $\models$ S

  Two approaches:

Reasoning Tasks

- Model finding

  KB = background knowledge

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  A kind of constraint satisfaction

- Deduction

  S = question

  Prove that KB $\models$ S

  Two approaches:

  - Rules to derive new formulas from old (inference)
  - Show (KB $\wedge \neg$ S) is unsatisfiable

Special Syntactic Forms

- General Form:

  $((q \wedge \neg r) \rightarrow s)) \wedge \neg (s \wedge t)$

- Conjunction Normal Form (CNF)

  $(\neg q \vee r \vee s) \wedge (\neg s \vee \neg t)$

  Set notation: $\{ (\neg q, r, s), (\neg s, \neg t) \}$

  empty clause () = *false*

- Binary clauses: 1 or 2 literals per clause

  $(\neg q \vee r)$ $(\neg s \vee \neg t)$

- Horn clauses: 0 or 1 positive literal per clause

  $(\neg q \vee \neg r \vee s)$ $(\neg s \vee \neg t)$

  $(q \wedge r) \rightarrow s$ $(s \wedge t) \rightarrow$ *false*

Propositional Logic: **Inference**

A ***mechanical*** process for computing new sentences

1. Backward & Forward Chaining
2. Resolution (Proof by Contradiction)
3. Davis Putnam
4. WalkSat

Inference 1: Forward Chaining

Forward Chaining

Based on rule of ***modus ponens***

If know $P_1, \ldots, P_n$ & know $(P_1 \wedge \ldots \wedge P_n) \rightarrow Q$

Then can conclude Q

Backward Chaining: search

start from the query and go backwards

Analysis

- Sound?
- Complete?

Analysis

- Sound?
- Complete?

Can you prove

$$\{\} \models Q \lor \neg Q$$

Analysis

- Sound?
- Complete?

Can you prove

$$\{\} \models Q \vee \neg Q$$

- If KB has only Horn clauses & query is a single literal
  - Forward Chaining is complete
  - Runs linear in the size of the KB

Example

$P \Rightarrow Q$

$L \wedge M \Rightarrow P$

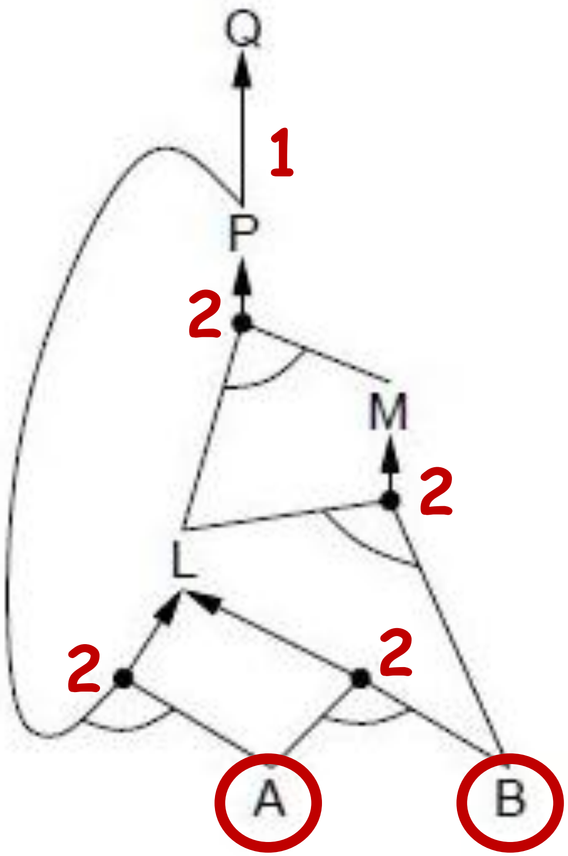
$B \wedge L \Rightarrow M$

$A \wedge P \Rightarrow L$

$A \wedge B \Rightarrow L$

A

B



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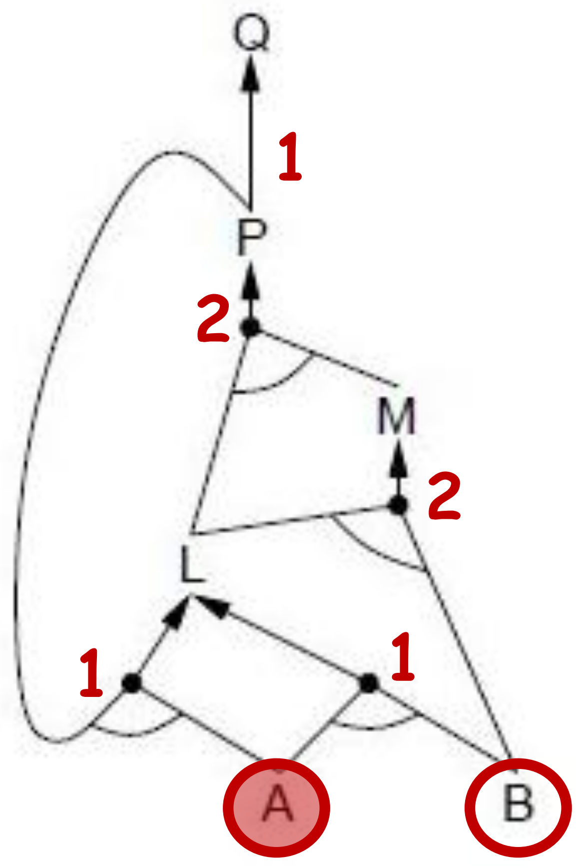

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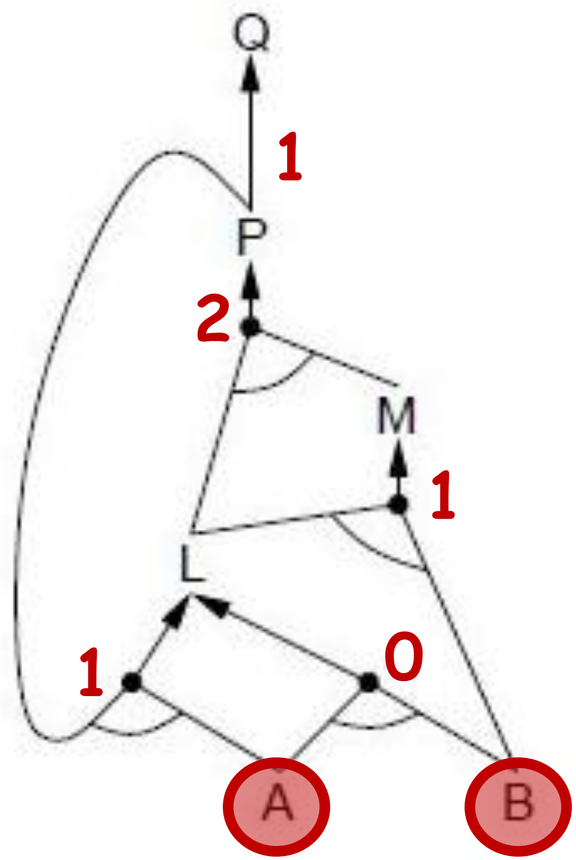

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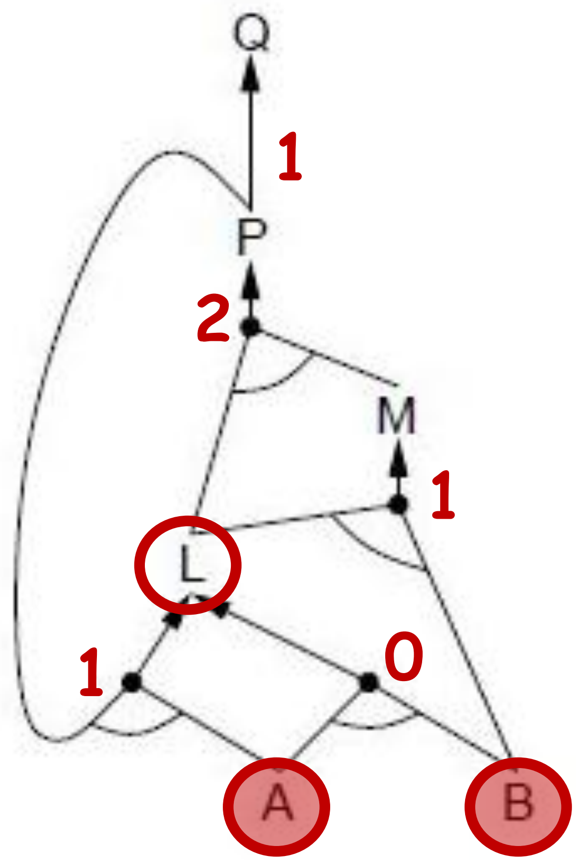

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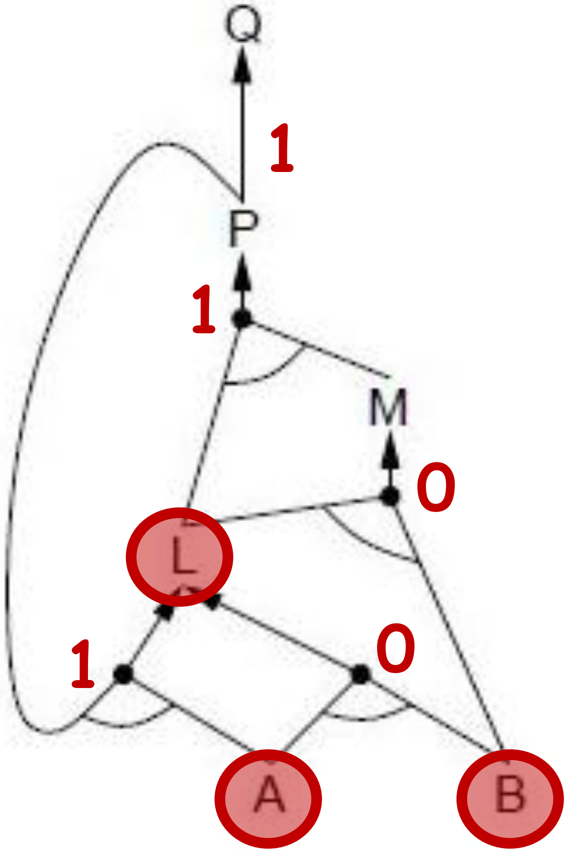

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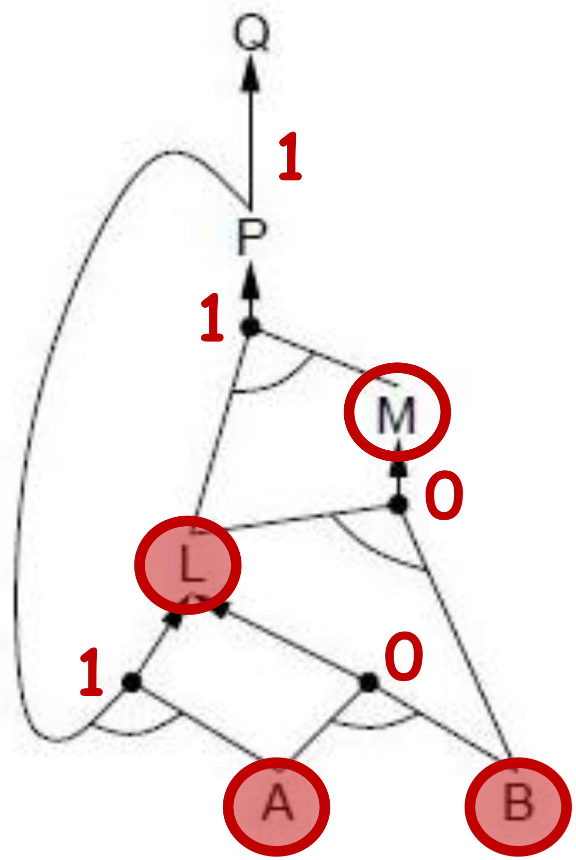

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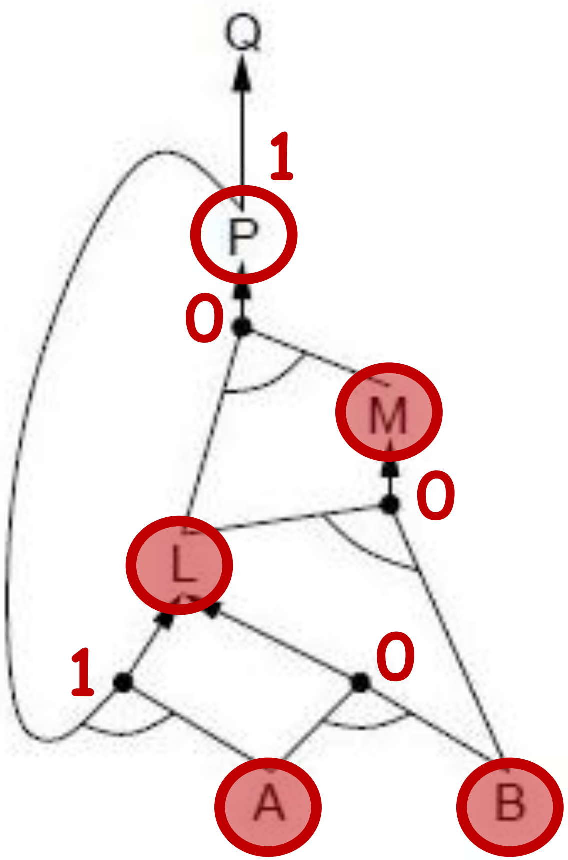

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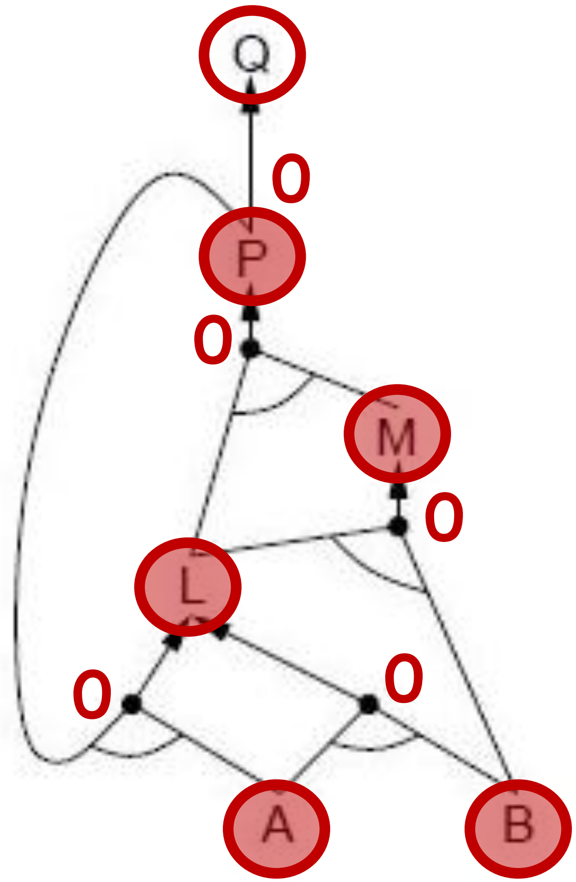

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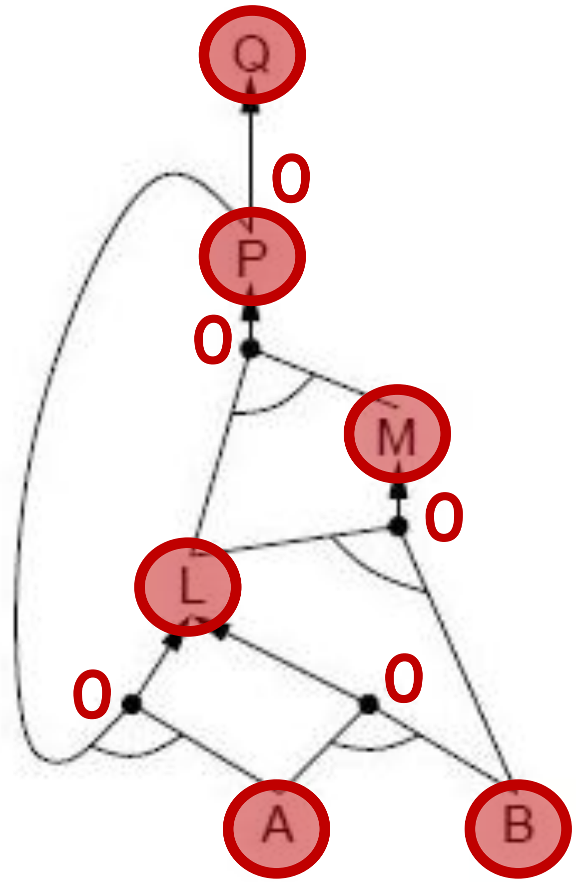

Propositional Logic: **Inference**

A ***mechanical*** process for computing new sentences

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Conversion to CNF

$B_{1,1} \Leftrightarrow (P_{1,2} \lor P_{2,1})$

1. Eliminate $\Leftrightarrow$, replacing $\alpha \Leftrightarrow \beta$ with $(\alpha \Rightarrow \beta) \land (\beta \Rightarrow \alpha)$.

   $(B_{1,1} \Rightarrow (P_{1,2} \lor P_{2,1})) \land ((P_{1,2} \lor P_{2,1}) \Rightarrow B_{1,1})$

2. Eliminate $\Rightarrow$, replacing $\alpha \Rightarrow \beta$ with $\neg\alpha \lor \beta$.

   $(\neg B_{1,1} \lor P_{1,2} \lor P_{2,1}) \land (\neg(P_{1,2} \lor P_{2,1}) \lor B_{1,1})$

3. Move $\neg$ inwards using de Morgan's rules and double-negation:

   $(\neg B_{1,1} \lor P_{1,2} \lor P_{2,1}) \land ((\neg P_{1,2} \land \neg P_{2,1}) \lor B_{1,1})$

4. Apply distributivity law ($\lor$ over $\land$) and flatten:

   $(\neg B_{1,1} \lor P_{1,2} \lor P_{2,1}) \land (\neg P_{1,2} \lor B_{1,1}) \land (\neg P_{2,1} \lor B_{1,1})$

Inference 2: Resolution

[Robinson 1965]

$$\{ (p \vee \alpha), (\neg p \vee \beta \vee \gamma) \} \vdash_R (\alpha \vee \beta \vee \gamma)$$

Inference 2: Resolution

[Robinson 1965]

$$\{ (p \vee \alpha), (\neg p \vee \beta \vee \gamma) \} \ \vdash_R (\alpha \vee \beta \vee \gamma)$$

Correctness

If S1 $\vdash_R$ S2 then S1 $\models$ S2

Refutation Completeness:

If S is unsatisfiable then S $\vdash_R$ ()

Resolution subsumes Modus Ponens

$A \rightarrow B, A \models B$

Resolution subsumes Modus Ponens

$A \rightarrow B, A \models B$

$(\neg A \vee B)$

Resolution subsumes Modus Ponens

$A \rightarrow B, A \models B$

$(\neg A \vee B)$ (A)

Resolution subsumes Modus Ponens

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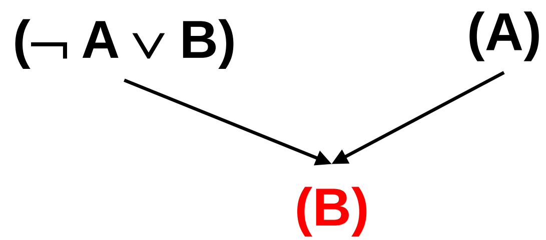

If Will *goes*, Jane will *go*

~W V J

If doesn't *go*, Jane will still *go*

W V J

Will Jane *go*?

|= J?

If Will *goes*, Jane will *go*

$\sim W \vee J$

If doesn't *go*, Jane will still *go*

$W \vee J$

Will Jane *go*?

$\models J$?

$J \vee J = J$

If Will goes, Jane will go

~W V J

If doesn't go, Jane will still go

W V J

Will Jane go?

|= J?

J V J =J

Don't need to use other equivalences if we use resolution in refutation style

~J

~W V J

W V J

~W

J

□

Resolution

If the unicorn is mythical, then it is immortal, but if it is not mythical, it is a mammal. If the unicorn is either immortal or a mammal, then it is horned.

Prove: the unicorn is horned.

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M = mythical
I = immortal
A = mammal
H = horned

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Prove: the unicorn is horned.

$(\neg A \vee H)$

$(\neg I \vee H)$

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$(M \vee A)$

$(\neg M \vee I)$

Resolution

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Prove: the unicorn is horned.

$(\neg A \vee H)$ $(\neg H)$ $(\neg I \vee H)$

$(M \vee A)$ $(\neg M \vee I)$

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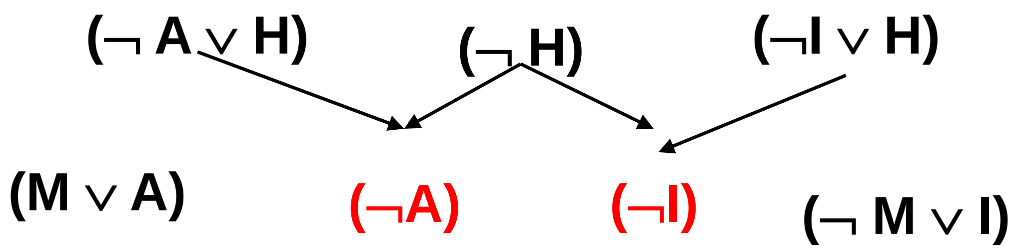

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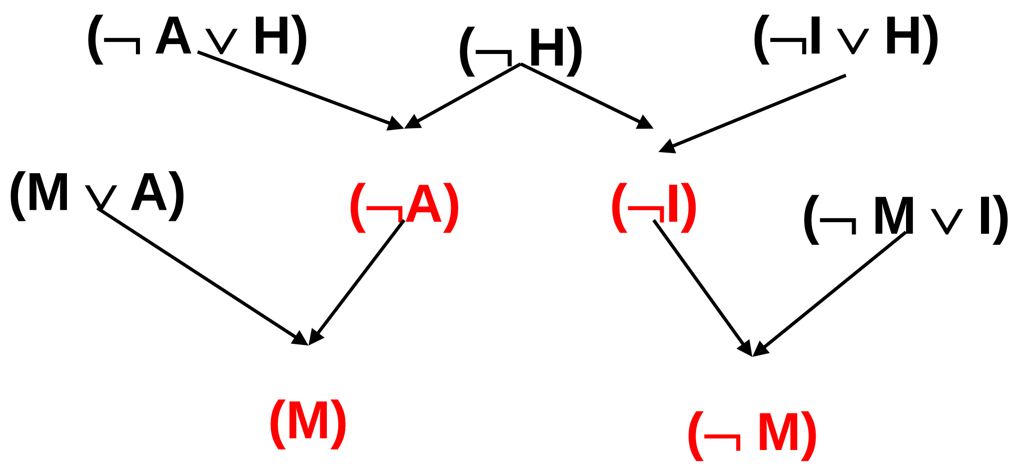

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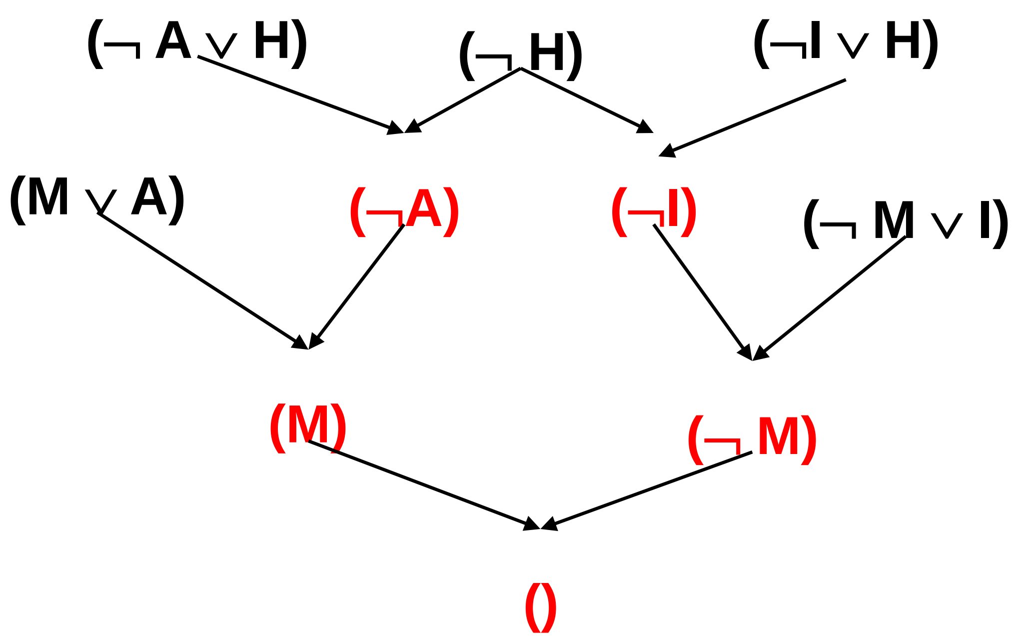

Search in Resolution

- Convert the database into clausal form D_c
- Negate the goal first, and *then* convert it into clausal form D_G
- Let $D = D_c + D_G$
- Loop
  - Select a pair of Clauses C1 and C2 from D
    - Different control strategies can be used to select C1 and C2 to reduce number of resolutions tries
  - Resolve C1 and C2 to get C12
  - If C12 is empty clause, QED!! Return Success (We proved the theorem;)
  - D = D + C12
- Out of loop but no empty clause. Return "Failure"
  - Finiteness is guaranteed if we make sure that:
    - we never resolve the same pair of clauses more than once;
    - we use factoring, which removes multiple copies of literals from a clause (e.g. QVPVP => QVP)

Idea 1: Set of Support: At least one of C1 or C2 must be either the goal clause or a clause derived by doing resolutions on the goal clause (*COMPLETE*)

Idea 2: Linear input form: Atleast one of C1 or C2 must be one of the clauses in the input KB (*INCOMPLETE*)

Model Finding

- Find assignments to variables that makes a formula true
- a CSP

Inference 3: Model Enumeration

```
for (m in truth assignments){
   if  (m makes Φ true)
   then return "Sat!"
}
 return "Unsat!"
```

Inference 4: DPLL
(Enumeration of ***Partial*** Models)

[Davis, Putnam, Loveland & Logemann 1962]

Version 1

```
dpll_1(pa){
  if (pa makes F false) return false;
  if (pa makes F true) return true;
  choose P in F;
  if (dpll_1(pa ∪ {P=0})) return true;
  return dpll_1(pa ∪ {P=1});
}
```

Returns true if F is satisfiable, false otherwise

DPLL Version 1

$(a \vee b \vee c)$

$(a \vee \neg b)$

$(a \vee \neg c)$

$(\neg a \vee c)$

DPLL Version 1

$(a \vee b \vee c)$

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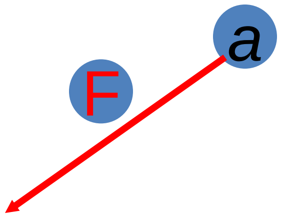

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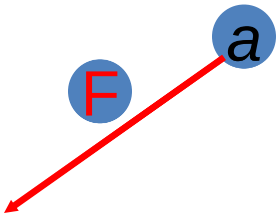


$(F \vee b \vee c)$

$(F \vee \neg b)$

$(F \vee \neg c)$

$(T \vee c)$

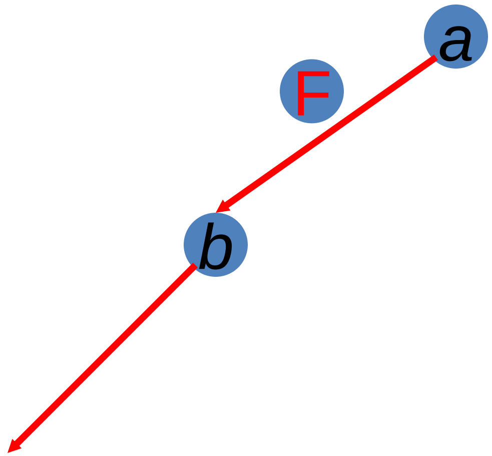
DPLL Version 1

(F ∨ F ∨ *c*)

(F ∨ T)

(F ∨ ¬*c*)

(T ∨ *c*)



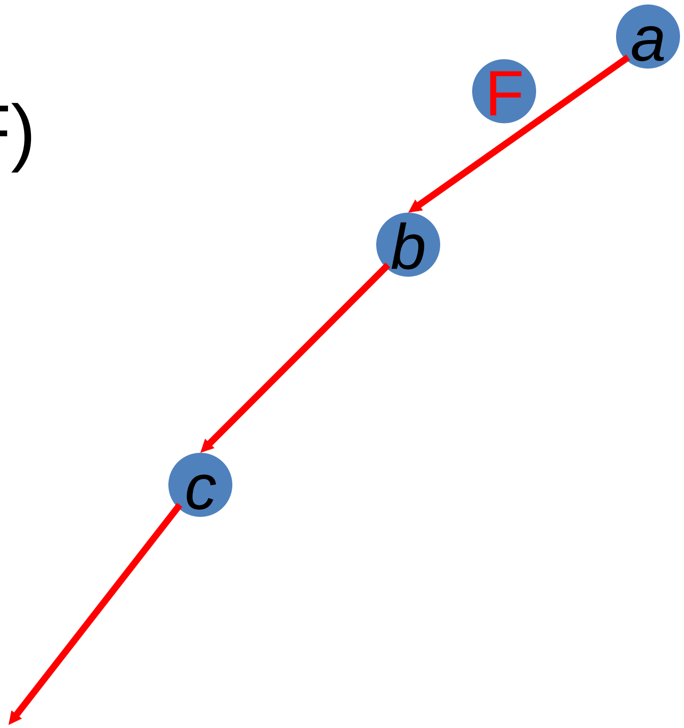
DPLL Version 1

$(F \vee F \vee F)$

$(F \vee T)$

$(F \vee T)$

$(T \vee F)$



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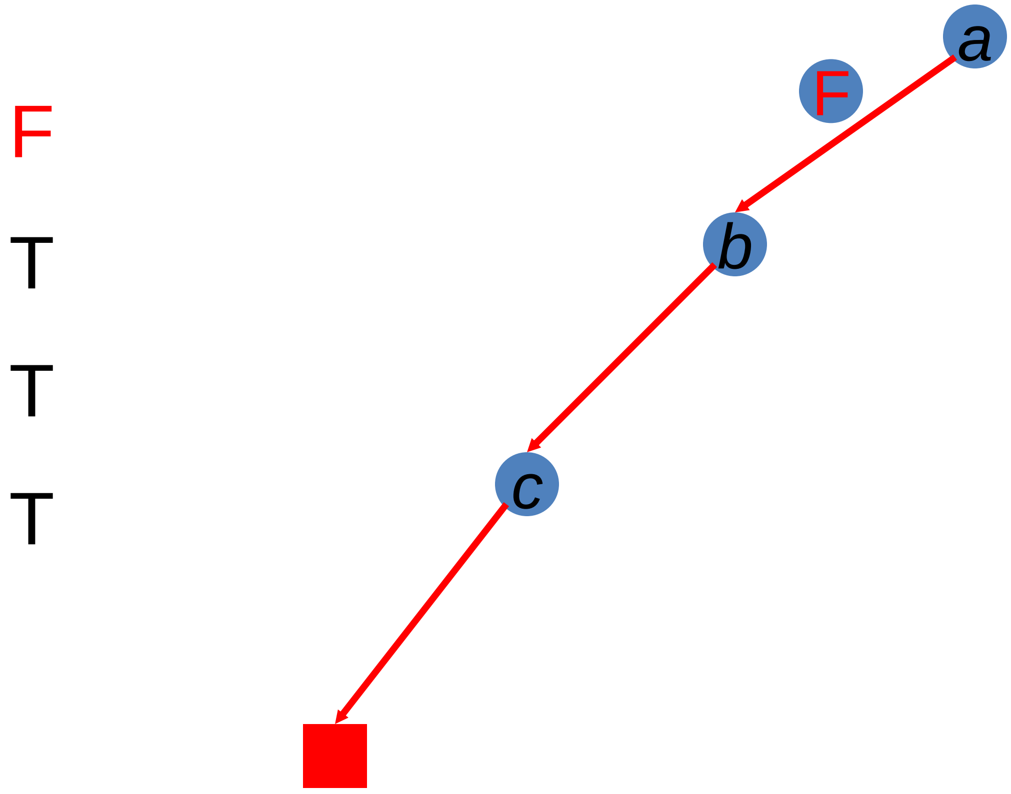


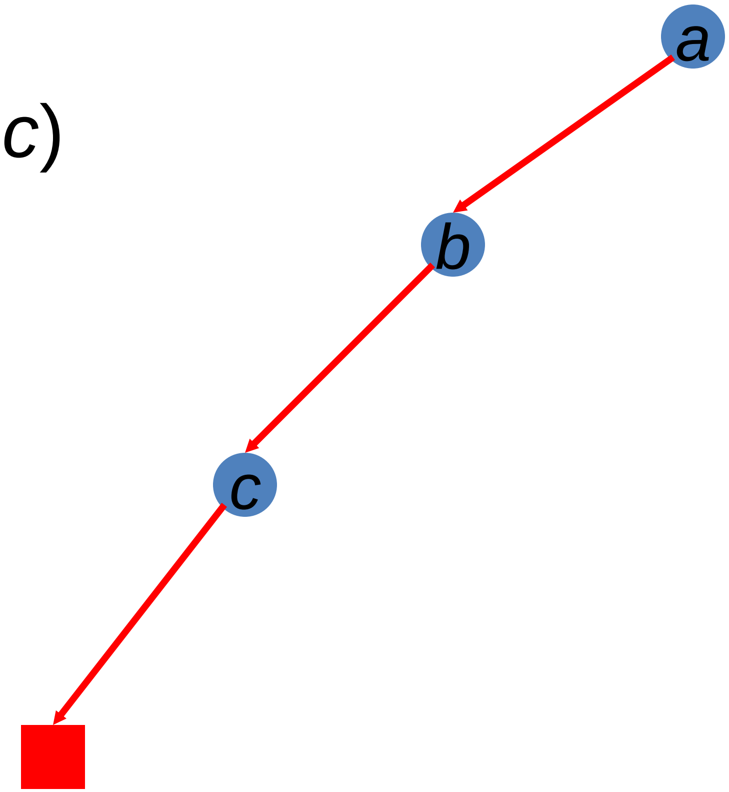
DPLL Version 1

$(a \vee b \vee c)$

$(a \vee \neg b)$

$(a \vee \neg c)$

$(\neg a \vee c)$



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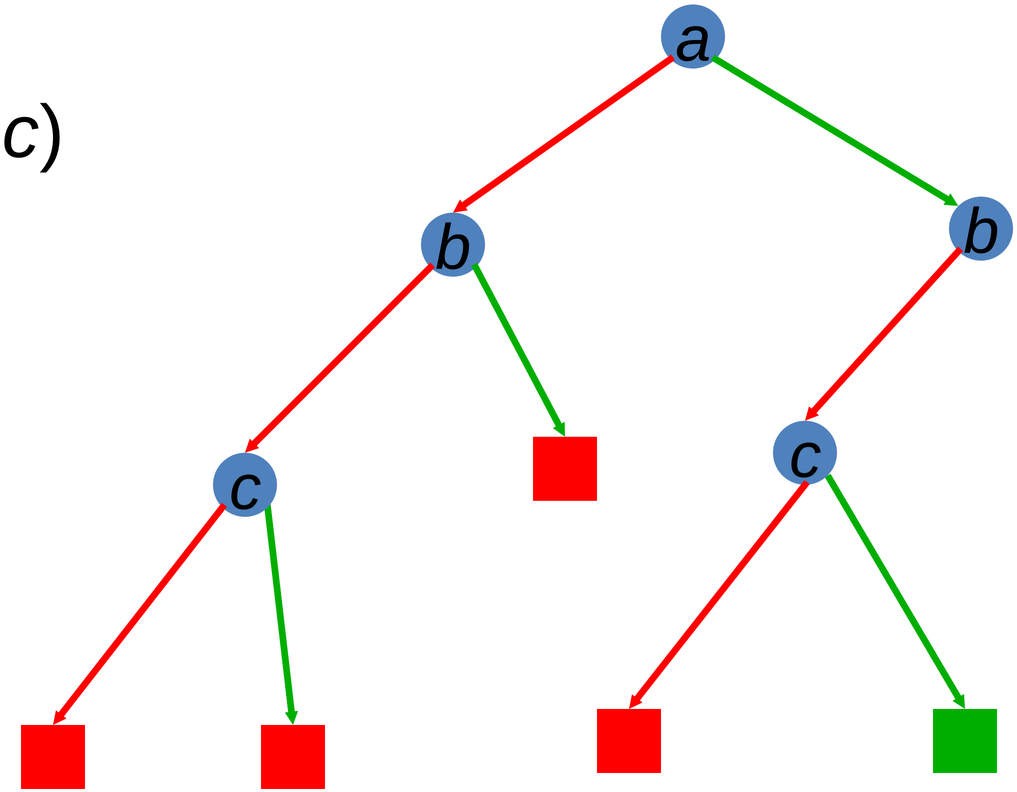


DPLL as Search

- Search Space?
- Algorithm?

Improving DPLL

If literal L_1 is true, then clause $(L_1 \vee L_2 \vee \ldots)$ is true

If clause C_1 is true, then $C_1 \wedge C_2 \wedge C_3 \wedge \ldots$ has the same value as $C_2 \wedge C_3 \wedge \ldots$

Therefore: Okay to delete clauses containing true literals!

If literal L_1 is false, then clause $(L_1 \vee L_2 \vee L_3 \vee \ldots)$ has the same value as $(L_2 \vee L_3 \vee \ldots)$

Therefore: Okay to shorten clauses containing false literals!

If literal L_1 is false, then clause (L_1) is false

Therefore: the empty clause means false!

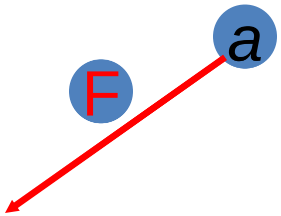
DPLL version 2

```
dpll_2(F, literal){




  choose V in F;
  if (dpll_2(F, ¬V))return true;
  return dpll_2(F, V);
}
```

DPLL version 2

```
dpll_2(F, literal){
  remove clauses containing literal
  if (F contains no clauses)return true;
  shorten clauses containing ¬literal
  if (F contains empty clause)
     return false;
  choose V in F;
  if (dpll_2(F, ¬V))return true;
  return dpll_2(F, V);
}
```

DPLL Version 2



$(F \vee b \vee c)$

$(F \vee \neg b)$

$(F \vee \neg c)$

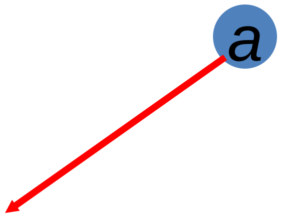
$(T \vee c)$

DPLL Version 2

$(b \vee c)$

$(\neg b)$

$(\neg c)$

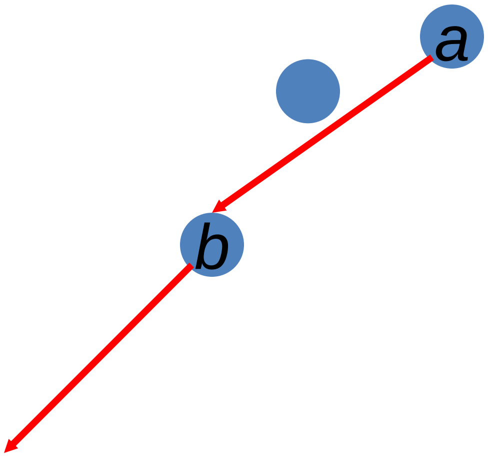


DPLL Version 2

($F \vee c$)

(T)

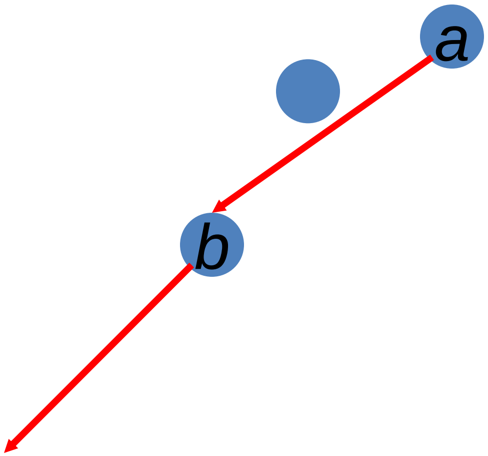
($\neg c$)



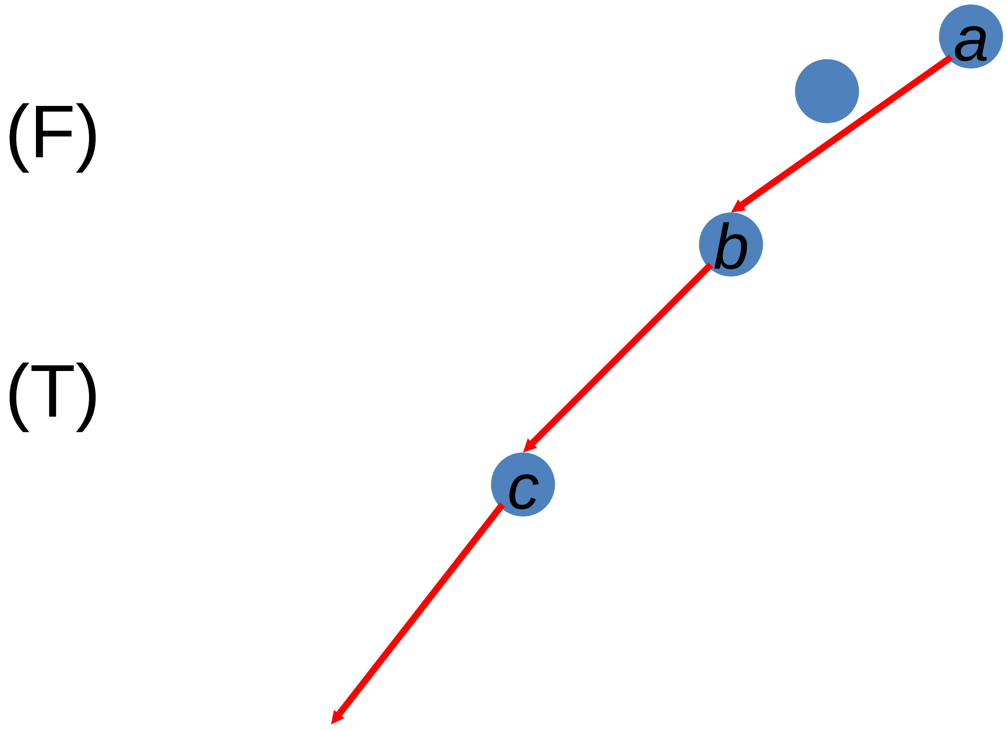
DPLL Version 2

(*c*)

(¬*c*)



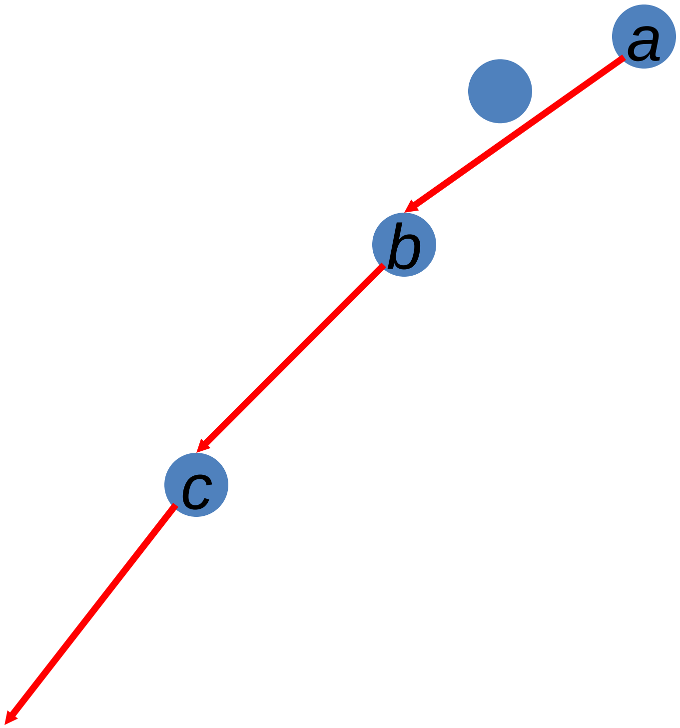
DPLL Version 2



DPLL Version 2

()

Empty clause!



Structure in Clauses

- Unit Literals

  A literal that appears in a singleton clause

  $\{\{\neg b\ c\}\{\neg c\}\{a\ \neg b\ e\}\{d\ b\}\{e\ a\ \neg c\}\}$

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  {{a ¬b c}   {¬a ¬b e}   {e a ¬c}}

In Other Words

Formula $(L) \wedge C_2 \wedge C_3 \wedge ...$ is only true when literal L is true

Therefore: Branch immediately on unit literals!

May view this as adding constraint propagation techniques into play

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Therefore: Branch immediately on unit literals!

If literal L does not appear negated in formula F, then setting L true preserves satisfiability of F

Therefore: Branch immediately on pure literals!

May view this as adding constraint propagation techniques into play

DPLL (previous version)

Davis – Putnam – Loveland – Logemann

```
dpll(F, literal){
  remove clauses containing literal
  if (F contains no clauses) return true;
  shorten clauses containing ¬literal
  if (F contains empty clause)
     return false;


  choose V in F;
  if (dpll(F, ¬V))return true;
  return dpll(F, V);
}
```

DPLL (for real!)

Davis – Putnam – Loveland – Logemann

```
dpll(F, literal){
  remove clauses containing literal
  if (F contains no clauses) return true;
  shorten clauses containing ¬literal
  if (F contains empty clause)
     return false;
  if (F contains a unit or pure L)
     return dpll(F, L);
  choose V in F;
  if (dpll(F, ¬V))return true;
  return dpll(F, V);
}
```

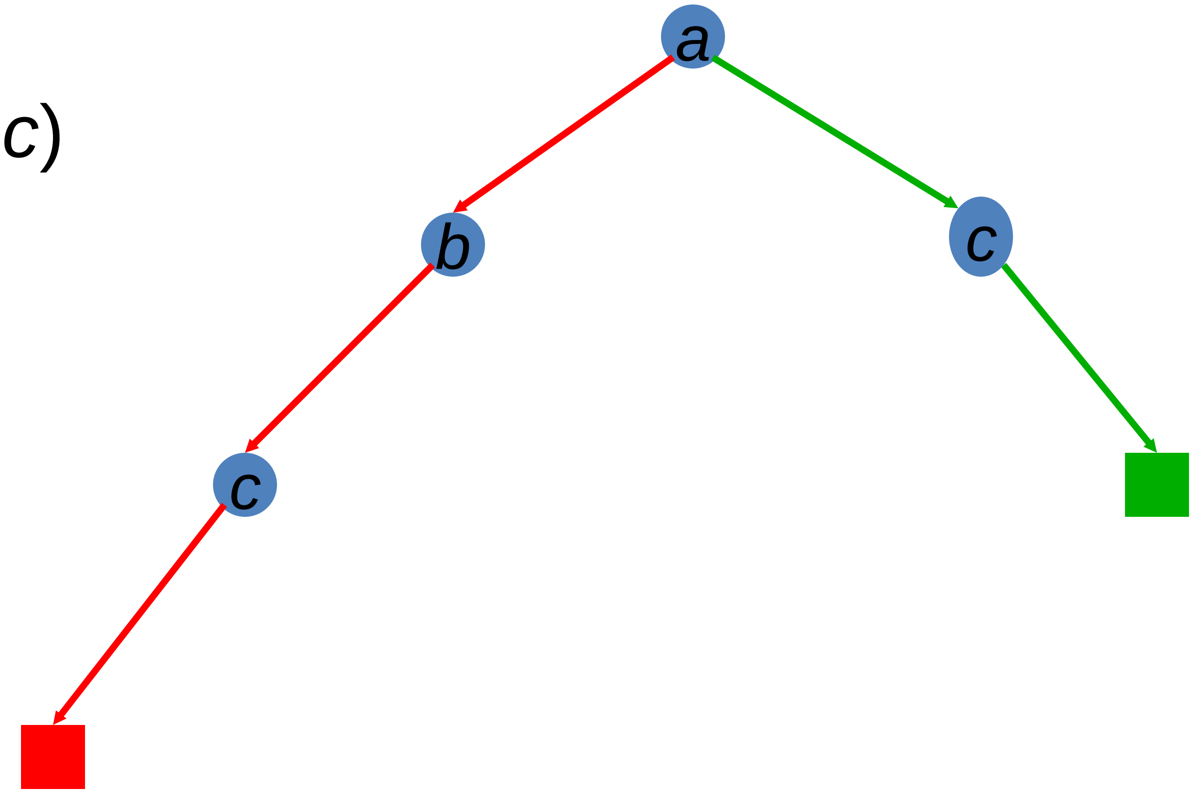
DPLL (for real)

$(a \vee b \vee c)$

$(a \vee \neg b)$

$(a \vee \neg c)$

$(\neg a \vee c)$



DPLL (for real!)

Davis – Putnam – Loveland – Logemann

```
dpll(F, literal){
   remove clauses containing literal
   if (F contains no clauses) return true;
   shorten clauses containing ¬literal
   if (F contains empty clause)
       return false;
   if (F contains a unit or pure L)
       return dpll(F, L);
   choose V in F;
   if (dpll(F, ¬V))return true;
   return dpll(F, V);
}
```

Where could we use a heuristic to further improve performance?

Heuristic Search in DPLL

- Heuristics are used in DPLL to select a (non-unit, non-pure) proposition for branching

- Idea: identify a most constrained variable

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Heuristic Search in DPLL

- Heuristics are used in DPLL to select a (non-unit, non-pure) proposition for branching
- Idea: identify a most constrained variable
  - Likely to create many unit clauses
- MOM's heuristic:
  - Most occurrences in clauses of minimum length

Success of DPLL

- 1962 – DPLL invented
- 1992 – 300 propositions
- 1997 – 600 propositions (satz)
- Additional techniques:
  - Learning conflict clauses at backtrack points
  - Randomized restarts
  - 2002 (zChaff) 1,000,000 propositions – encodings of hardware verification problems