Propositional Logic

Russell and Norvig:
Chapter 7, Sections 7.1 – 7.5.1

Slides by Jean-Claude Latombe, from an introductory AI course given at Stanford University. Used (and adapted) with permission.

Important Concepts in AI

- The Representation of Knowledge about the world

- The Reasoning Process to make use of it

Types of Agents

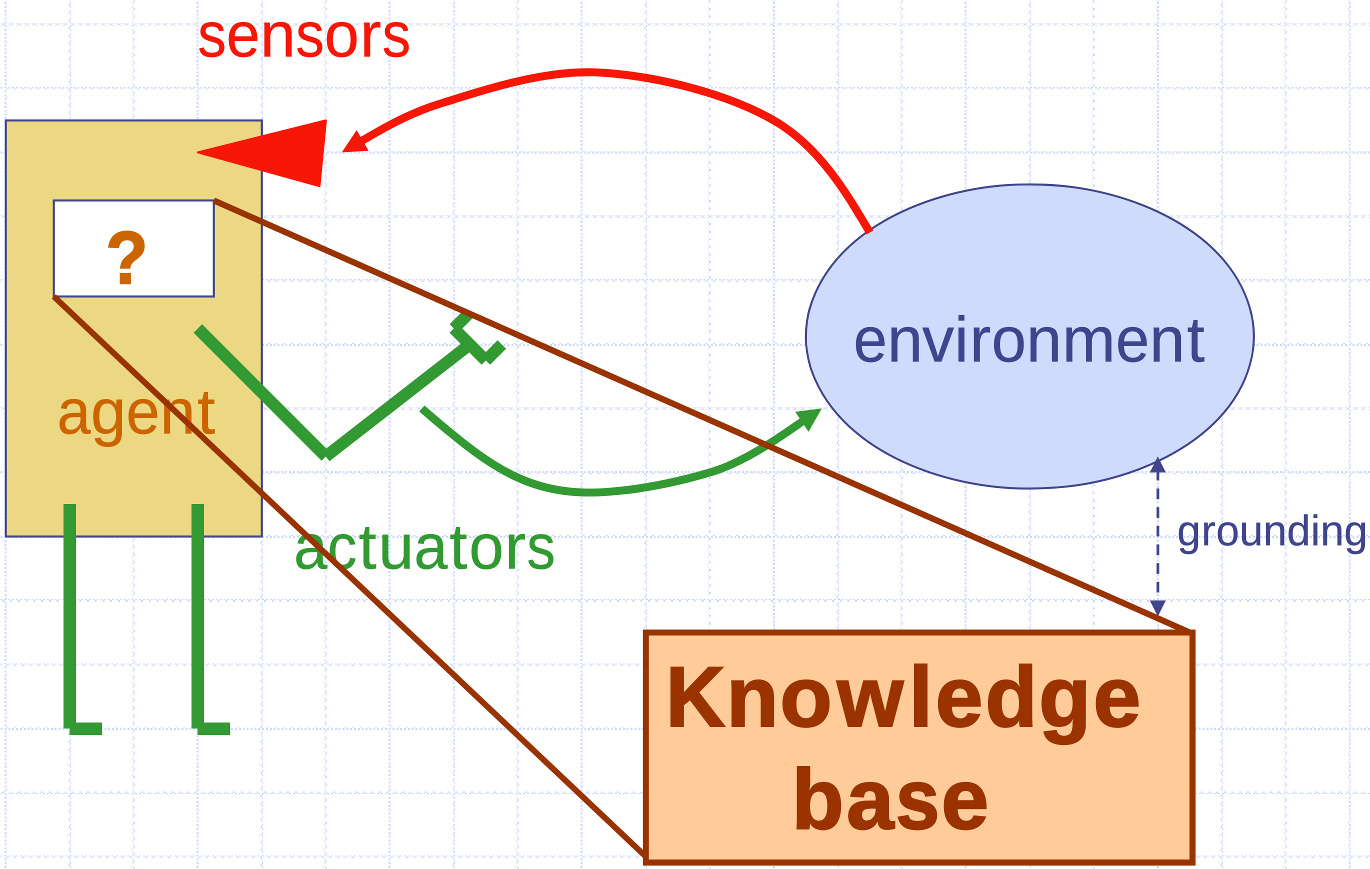
- Reflex Agent
  - Dumb luck
- Problem-solving Agent
  - Specific and inflexible
- Knowledge-based agent
  - General and flexible

Partially Seen Environments

- Knowledge-based Agents can combine
  - General Knowledge
  - Current Percepts

To infer hidden aspects!

Knowledge-Based Agent



Types of Knowledge

- Procedural, e.g.: functions
  Such knowledge can only be used in one way -- by executing it

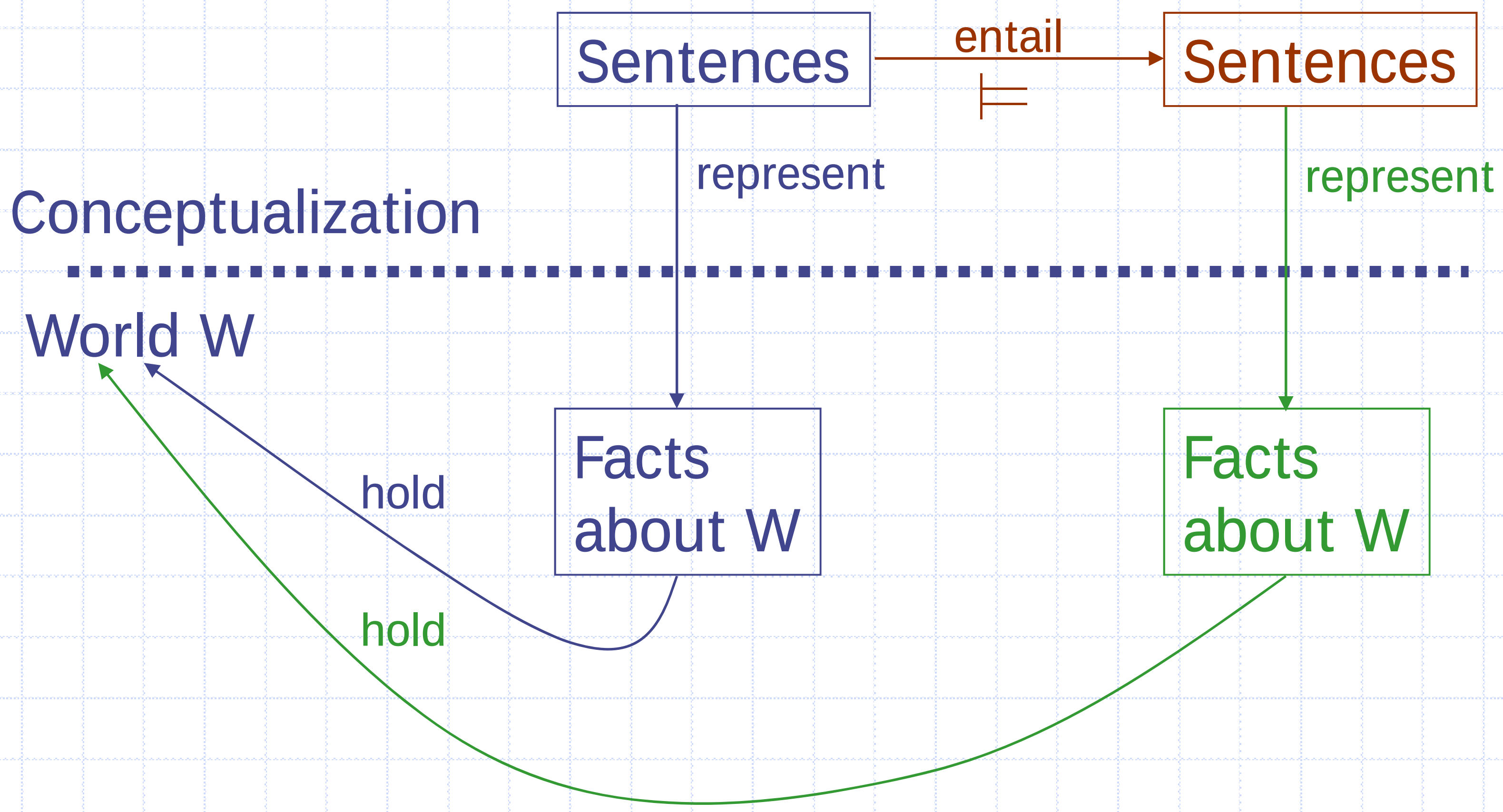
- Declarative, e.g.: constraints
  It can be used to perform many different sorts of inferences

Logic

Logic is a declarative language to:

- Assert sentences representing facts that hold in a world **W** (these sentences are given the value true)
- Deduce the true/false values to sentences representing other aspects of **W**

World-Representation



Examples of Logics

- Propositional calculus

  $A \wedge B \Rightarrow C$

- First-order predicate calculus

  $(\forall x)(\exists y)\ Mother(y,x)$

- Logic of Belief

  `B(John,Father(Zeus,Cronus))`

Symbols of PL

- Connectives: $\neg, \wedge, \vee, \Rightarrow, \Leftrightarrow$
- Propositional symbols:
  - Can be either true or false: P, Q, R, ...
  - Fixed meaning: *True*, *False*

Syntax of PL

- sentence $\rightarrow$ atomic sentence | complex sentence
- atomic sentence $\rightarrow$ *True* | *False* | P | Q | R | ...
- complex sentence $\rightarrow \neg$sentence
  | (sentence $\wedge$ sentence)
  | (sentence $\vee$ sentence)
  | (sentence $\Rightarrow$ sentence)
  | (sentence $\Leftrightarrow$ sentence)

Syntax of PL

- sentence → atomic sentence | complex sentence
- atomic sentence → *True* | *False* | P | Q | R | ...
- complex sentence → ¬sentence
  - | (sentence ∧ sentence)
  - | (sentence ∨ sentence)
  - | (sentence ⇒ sentence)
  - | (sentence ⇔ sentence)

- Examples:
  - $((P \wedge Q) \Rightarrow R)$
  - $(A \Rightarrow B) \vee (\neg C)$

Counter examples:

$(A \wedge \Rightarrow R)$

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

Order of Precedence

- $\neg \quad \wedge \quad \vee \quad \Rightarrow \quad \Leftrightarrow$
- Examples:
  - $\neg A \vee B \Rightarrow C$ is equivalent to $((\neg A) \vee B) \Rightarrow C$
  - $A \Rightarrow B \Rightarrow C$ is incorrect

$(A \Rightarrow B) \Rightarrow C$

$A \Rightarrow (B \Rightarrow C)$

Model

- Assignment of a truth value – *true* or *false* – to every atomic sentence
- Examples:
  - Let A, B, C, and D be the propositional symbols
  - m = {A=true, B=false, C=false, D=true} is a model
  - m' = {A=true, B=false, C=false} is not a model
- With n propositional symbols, one can define 2^n models

What Worlds Does a Model Represent?

A model represents any world in which some fact represented by a proposition A having the value *True* holds and some fact represented by a proposition B having the value *False* does not hold (where only A and B are symbols)

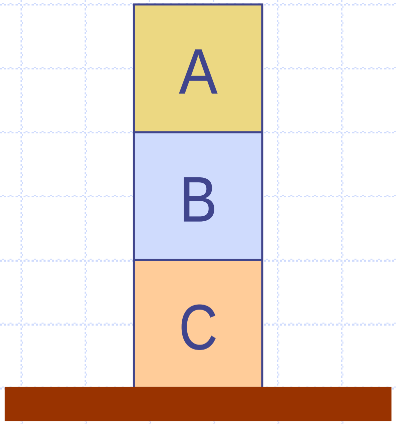
m={A=*True*, B=*False*} →
Any world where A represents a held fact and B represents a fact that doesn't hold

A model represents infinitely many worlds

Compare!

prop.symb.

- BLOCK(A), BLOCK(B), BLOCK(C)
- ON(A,B), ON(B,C), ONTABLE(C)
- ON(A,B) $\wedge$ ON(B,C)$\Rightarrow$ABOVE(A,C)
- $\square$ ABOVE(A,C)



- HUMAN(A), HUMAN(B), HUMAN(C)
- CHILD(A,B), CHILD(B,C), BLOND(C)
- CHILD(A,B) $\wedge$ CHILD(B,C)$\Rightarrow$GRAND-CHILD(A,C)
- $\square$ GRAND-CHILD(A,C)

Semantics of PL

- It specifies how to determine the truth value of any sentence in a model m
- The truth value of *True* is *True*
- The truth value of *False* is *False*
- The truth value of each atomic sentence is given by m
- The truth value of every other sentence is obtained recursively by using truth tables

Truth Tables

A	B	$\neg$A	A $\wedge$ B	A $\vee$ B	A$\Rightarrow$B
True	*True*	*False*	*True*	*True*	*True*
True	*False*	*False*	*False*	*True*	*False*
False	*False*	*True*	*False*	*False*	*True*
False	*True*	*True*	*False*	*True*	*True*

Truth Tables

A	B	$\neg$A	A $\wedge$ B	A $\vee$ B	A $\Rightarrow$ B
True	*True*	*False*	*True*	*True*	*True*
True	*False*	*False*	*False*	*True*	*False*
False	*False*	*True*	*False*	*False*	*True*
False	*True*	*True*	*False*	*True*	*True*

Truth Tables

A	B	¬A	A ∧ B	A ∨ B	A⇒B
True	*True*	*False*	*True*	*True*	*True*
True	*False*	*False*	*False*	*True*	*False*
False	*False*	*True*	*False*	*False*	*True*
False	*True*	*True*	*False*	*True*	*True*

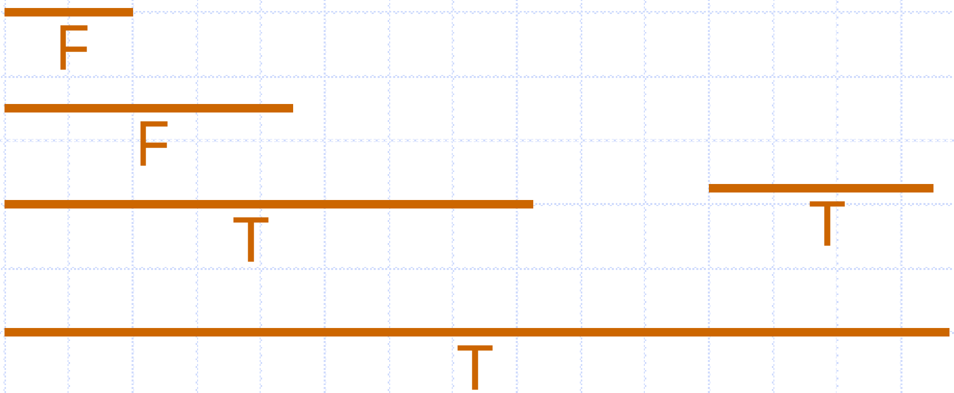
About$\Rightarrow$

- ODD(5)$\Rightarrow$CAPITAL(Japan,Tokyo)
- EVEN(5)$\Rightarrow$SMART(Sam)
- Read A$\Rightarrow$B as:
  "If A IS *True*, then I claim that B is *True*, otherwise I make no claim."

Example

Model: A= *True*, B= *False*, C= *False*, D= *True*

$$(\neg A \vee B \Rightarrow C) \Rightarrow D \wedge A$$



Definition: If a sentence **s** is true in a model **m**, then **m** is said to be a **model** of **s**

A Small Knowledge Base

1. $Battery\text{-}OK \land Bulbs\text{-}OK \Rightarrow Headlights\text{-}Work$
2. $Battery\text{-}OK \land Starter\text{-}OK \land \neg Empty\text{-}Gas\text{-}Tank \Rightarrow Engine\text{-}Starts$
3. $Engine\text{-}Starts \land \neg Flat\text{-}Tire \Rightarrow Car\text{-}OK$
4. $Headlights\text{-}Work$
5. $\neg Car\text{-}OK$

Sentences 1, 2, and 3 → Background knowledge

Sentences 4 and 5 → Observed knowledge

Model of a KB

- Let KB be a set of sentences
- A model m is a model of KB iff it is a model of all sentences in KB, that is, all sentences in KB are true in m

Satisfiability of a KB

A KB is satisfiable iff it admits at least one model; otherwise it is unsatisfiable

KB1 = $\{P, \neg Q \wedge R\}$ is satisfiable

KB2 = $\{\neg P \vee P\}$ is satisfiable

valid sentence or tautology

KB3 = $\{P, \neg P\}$ is unsatisfiable

Logical Entailment

- KB : set of sentences
- α : arbitrary sentence
- KB entails α – written KB $\models \alpha$ – iff every model of KB is also a model of α

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- KB : set of sentences
- α : arbitrary sentence
- KB **entails** α – written KB $\models \alpha$ – iff every model of KB is also a model of α
- Alternatively, KB $\models \alpha$ iff
  - $\{KB, \neg\alpha\}$ is unsatisfiable
  - $KB \Rightarrow \alpha$ is valid

Logical Equivalence

- Two sentences α and β are logically equivalent – written $\alpha \equiv \beta$ -- iff they have the same models, i.e.:

$$\alpha \equiv \beta \text{ iff } \alpha \models \beta \text{ and } \beta \models \alpha$$

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- Examples:
  - $(\alpha \land \beta) \equiv (\beta \land \alpha)$
  - $\alpha \Rightarrow \beta \equiv \neg\alpha \lor \beta$
  - $\neg(\alpha \land \beta) \equiv \neg\alpha \lor \neg\beta$
  - $\neg(\alpha \lor \beta) \equiv \neg\alpha \land \neg\beta$

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- Examples:
  - $(\alpha \wedge \beta) \equiv (\beta \wedge \alpha)$
  - $\alpha \Rightarrow \beta \equiv \neg\alpha \vee \beta$
  - $\neg(\alpha \wedge \beta) \equiv \neg\alpha \vee \neg\beta$
  - $\neg(\alpha \vee \beta) \equiv \neg\alpha \wedge \neg\beta$
- One can always replace a sentence by an equivalent one in a KB

Inference Rule

- An inference rule $\{\xi, \psi\} \vdash \varphi$ consists of 2 sentence patterns ξ and ψ called the conditions and one sentence pattern φ called the conclusion

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- An inference rule $\{\xi, \psi\} \vdash \varphi$ consists of 2 sentence patterns ξ and ψ called the conditions and one sentence pattern φ called the conclusion
- If ξ and ψ match two sentences of KB then the corresponding φ can be inferred according to the rule

Example: Modus Ponens

$$\{ \alpha \Rightarrow \beta \ , \alpha \} \vdash \beta$$

$$\{\xi, \psi\} \vdash \varphi$$

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$$\{\xi,\ \psi\} \vdash \varphi$$

Battery-OK $\wedge$ Bulbs-OK $\Rightarrow$ Headlights-Work

Battery-OK $\wedge$ Starter-OK $\wedge$ $\neg$Empty-Gas-Tank $\Rightarrow$ Engine-Starts

Engine-Starts $\wedge$ $\neg$Flat-Tire $\Rightarrow$ Car-OK

Battery-OK $\wedge$ Bulbs-OK

Example: Modus Ponens

$$\{\ \alpha \Rightarrow \beta\ ,\ \alpha\ \}\ \vdash\ \beta$$

$$\{\xi,\ \psi\} \vdash \varphi$$

Battery-OK ∧ Bulbs-OK ⇒ Headlights-Work

Battery-OK ∧ Starter-OK ∧ ¬Empty-Gas-Tank ⇒ Engine-Starts

Engine-Starts ∧ ¬Flat-Tire ⇒ Car-OK

Battery-OK ∧ Bulbs-OK

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Battery-OK $\wedge$ Bulbs-OK

Headlights-Work

Example: Modus Tolens

$$\{ \alpha \Rightarrow \beta \ , \neg \beta \} \vdash \neg \alpha$$

Engine-Starts $\wedge \neg$Flat-Tire$\Rightarrow$Car-OK
$\neg$Car-OK

Example: Modus Tolens

$$\{ \alpha \Rightarrow \beta \ , \neg \beta \} \ \vdash \ \neg \alpha$$

Engine-Starts ∧ ¬Flat-Tire ⇒ Car-OK

¬Car-OK

¬(Engine-Starts ∧ ¬Flat-Tire)

Example: Modus Tolens

$$\{ \alpha \Rightarrow \beta \ , \neg \beta \} \ \vdash \ \neg \alpha$$

Engine-Starts $\wedge \neg$Flat-Tire $\Rightarrow$ Car-OK
$\neg$Car-OK
$\neg$(Engine-Starts $\wedge \neg$Flat-Tire) $\equiv \neg$Engine-Starts $\vee$ Flat-Tire

Other Examples

- $\{\alpha,\beta\} \vdash \alpha \wedge \beta$
- $\{\alpha\wedge\beta,.\} \vdash \alpha$
- $\{\alpha\wedge\beta,.\} \vdash \beta$
- Etc ...

Inference

- I: Set of inference rules
- KB: Set of sentences
- Inference is the process of applying successive inference rules from I to KB, each rule adding its conclusion to KB

Example

1. Battery-OK ∧ Bulbs-OK⇒Headlights-Work
2. Battery-OK ∧ Starter-OK ∧ ¬Empty-Gas-Tank⇒Engine-Starts
3. Engine-Starts ∧ ¬Flat-Tire⇒Car-OK
4. Headlights-Work
5. Battery-OK
6. Starter-OK
7. ¬Empty-Gas-Tank
8. ¬Car-OK

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2. Battery-OK $\wedge$ Starter-OK $\wedge \neg$Empty-Gas-Tank $\Rightarrow$ Engine-Starts
3. Engine-Starts $\wedge \neg$Flat-Tire $\Rightarrow$ Car-OK
4. Headlights-Work
5. Battery-OK
6. Starter-OK
7. $\neg$Empty-Gas-Tank
8. $\neg$Car-OK
9. Battery-OK $\wedge$ Starter-OK $\leftarrow$ (5+6)

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9. Battery-OK $\wedge$ Starter-OK $\leftarrow$ (5+6)
10. Battery-OK $\wedge$ Starter-OK $\wedge \neg$Empty-Gas-Tank $\leftarrow$ (9+7)

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4. Headlights-Work
5. Battery-OK
6. Starter-OK
7. ¬Empty-Gas-Tank
8. ¬Car-OK
9. Battery-OK ∧ Starter-OK ← (5+6)
10. Battery-OK ∧ Starter-OK ∧ ¬Empty-Gas-Tank ← (9+7)
11. Engine-Starts ← (2+10)

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12. ¬Engine-Starts ∨ Flat-Tire ← (3+8)

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12. $\neg$Engine-Starts $\vee$ Flat-Tire $\leftarrow$ (3+8) $\equiv$ Engine-Starts $\Rightarrow$ Flat-Tire

Example

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3. Engine-Starts ∧ ¬Flat-Tire ⇒ Car-OK
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11. Engine-Starts ← (2+10)
12. Engine-Starts ⇒ Flat-Tire ← (3+8)
13. Flat-Tire ← (11+12)

Soundness

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- All inference rules previously given are sound, e.g.:
  modus ponens: $\{\alpha \Rightarrow \beta , \alpha\} \vdash \beta$
- The following rule:

  $$\{\alpha \lor \beta , .\} \vdash \neg\alpha \lor \neg\beta$$

  ...is unsound

Completeness

- A set of inference rules is complete if every entailed sentences can be obtained by applying some finite succession of these rules
- Modus ponens alone is not complete, e.g.:
  from $A \Rightarrow B$ and $\neg B$, we cannot get $\neg A$
  (needed Modus Tolens for that)

Proof

The proof of a sentence α from a set of sentences KB is the derivation of α by applying a series of sound inference rules

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11. Engine-Starts $\leftarrow$ (2+10)
12. Engine-Starts $\Rightarrow$ Flat-Tire $\leftarrow$ (3+8)
13. Flat-Tire $\leftarrow$ (11+12)

$\Rightarrow$ Connective symbol (implication)

$\models$ Logical entailment

KB $\models \alpha$ iff KB $\Rightarrow \alpha$ is valid

$\vdash$ Inference

$\vdash$ ~ $\models$ if $\vdash$ sound and complete

Summary

- Knowledge representation
- Propositional Logic
- Truth tables
- Model of a KB
- Satisfiability of a KB
- Logical entailment
- Inference rules
- Proof