

*Notes on Knowledge Representation and  
Reasoning*  
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## Section 1 – Introduction to KRR

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### - 1 - Introduction to Knowledge Representation and Reasoning.

Knowledge Representation and Reasoning (KRR) is a branch of Artificial Intelligence focused on understanding how knowledge, whose meaning will be soon clarified, can be represented symbolically and manipulated automatically by reasoning programs.

Formally, knowledge is defined as the relationship existing between a *knower* and a proposition; that is, the idea expressed by a simple declarative sentence (eg. “Mark will come to the party”). To represent and manipulate knowledge, which is our end goal, we have to understand what reasoning is. Let  $p_1, p_2, \dots, p_n$  be a sequence of premises; we define *reasoning* as the process which, from the premises  $p_1, \dots, p_n$  allows one to draw a conclusion. Later on we discuss the logic formalization of reasoning.

Throughout this notes we use a “logic language”, later discussed, known as First Order Logic (FOL). Similarly to any other language it has its own:

- *syntax*: the set of symbols and rules of the language;
- *semantic*: the meaning of syntactically correct sentences; and
- *pragmatics*: how context and habits contribute to the meaning.

The next two sections cover all the type of reasoning. Precisely, we first discuss of all those aspects of the human reasoning that lead to an incorrect reasoning, we then focus on the three main types of correct reasoning.

#### - 1.1 - Sources of incorrect reasoning.

At the source of an incorrect (human) reasoning there are mainly three causes: *fallacies*, *biases* and *paradoxes*. Each of these groups a set of causes that we discuss briefly.

**Remark.** The lists we provide for each (fallacies, biases and paradoxes) is not exhaustive at all. More on these can be found easily online.

##### - 1.1.1 - Fallacies.

The concept of *fallacy* is straightforward. It is an argument that, despite sounding convincing, is invalid.

###### **Example**

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Consider the sentence “A pencil isn’t an animal. All animals feed. Therefore a pencil doesn’t feed”. Though both premises are true, and therefore the conclusion, the overall sentence is non-sensical.

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We can distinguish several types of fallacies, some of which are listed below.

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- Fallacy of composition (*compositio*): attributes to an entity as a whole some property valid for its parts.

“The product is on sale at a price of 10,000 euros, payable in small installments of only 100 euros each. Therefore the total price is moderate.”

- Fallacy of division (*divisio*): attributes to the individual parts a property that is valid for the whole entity

“A truck is heavy. Therefore each of its component is heavy.”

- Fallacy of relevance: derives a conclusion from premises that are irrelevant.

It has different forms. We list them below.

- Argumentum ad hominem: discredits a thesis in order to deduce its falsity.
- Tu quoque: the one proposing a thesis does the opposite of what he wants to prove.
- Ad vericundum: the thesis is supposed to be true just because credit is given to those proposing it.
- Ad populum: accepts a thesis simply because it's accepted by the majority.
- Straw Man: creates a distorted version of a thesis, to refute it.
- Ad ignorantiam: supports a thesis by refuting the arguments in favor of the opposite thesis.
- Petitio principi: the thesis itself is hidden within the premises.
- False dichotomy: present two solutions to the problem, as if these are the only ones.
- Non causa pro causa: fix two peculiar characteristics and derive that the first causes the second one.

### - 1.1.2 - biases.

We as humans are subject to biases, which are systematic pattern deviation from the norm or rationality in the mental process of judgement. As for fallacies, we can distinguish several forms of bias; and interestingly enough biases are at the base of some of the fallacies we discussed previously.

As done for fallacies, we list some of the most common types of biases, to give the reader an idea of what these are concretely.

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- Confirmation bias: is a mental process that consists in selecting the information possessed in order to place greater attention, and therefore greater credibility, on those that confirm one's beliefs.
- Belief bias: is the tendency to judge the correctness of an argument based on the correctness of the conclusion.
- Availability bias (studied by Kahneman<sup>1</sup> and Tversky) is the tendency that leads us to make judgments on the basis of the most available examples and/or information, which most easily and vividly come to mind.

### - 1.1.3 - paradoxes.

The concept of paradox is well known to everybody, though in the context of logic it's usually misleading; by this we refer to the fact that some of those that are generally considered paradoxes, are not. For instance, let us consider Epimenides's liar paradox:

“All Cretans always lie.”

Since Epimenides was Cretan, he himself would be lying. Thus, the phrase “All Cretans always lie” cannot be true, cause it would contradict itself. Therefore, it's simply false.

More often than not paradoxes derive from the fact that semantic meaning is attributed to a sentence that refers to itself. This is what we call self-referentiality. This problem with self-referentiality was later understood by *Russell*.

### - 1.2 - Correct forms of reasoning.

One can reach a correct reasoning through three approaches: *deduction*, *abduction* and *induction*. We discuss each of these in the next few sections, but we focus mainly on deduction in the rest of these notes.

We note that, in the case of formal reasoning, frequent mistakes usually concern conditional statements, i.e., sentences of the form “If A, then B” or those that can somehow be transformed into one of this type. We call A and B, respectively, *antecedent* and *consequent*.

“If it rains, we always take the umbrella. Yesterday we took the umbrella, so yesterday it rained.”

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<sup>1</sup>For their result, Kahneman was praised with the nobel (Tversky was dead at that time). On the topic of biases, we suggest reading “Thinking, Fast and Slow” by Kahneman.

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### - 1.2.1 - Deduction.

Let us consider again the sentence:

“If it rains, we always take the umbrella. Yesterday we took the umbrella, so yesterday it rained.”

Is it necessary true? What if we took the umbrella to repair it?

This kind of reasoning is called deduction; that is, deduction is the process that from a “rule” (the conditional) derives a conclusion.

The above is an example of what we call *affirming the consequent*; that is, we deduce that A is true knowing that B is true, when there exist a conditional statements involving A and B. As its counterpart we have the *denying the antecedent* fallacy, in which we deduce the falsity of B by knowing with certainty that A is not true.

Given a conditional sentence, the two correct ways to apply deduction are called

- modus ponens: we know that A is true and deduce that B is also true.
- modus tollens: we know that B is false and deduce that A is also false.

### - 1.2.2 - Abduction and induction.

For what we have said about deduction, is easy to understand that it with logical inferences that are certain. Abduction and induction on the other hand cover probable inferences. That is, deduction differs from both, abduction and induction, by the degree of trust we put in the inference. To see such difference, see how the sentence

“If it rains, we always take the umbrella. Yesterday we took the umbrella, so yesterday it rained.”

becomes the sentence

“If it rains, we always take the umbrella. Yesterday we took the umbrella, so yesterday it probably rained.”

in the abduction case, and

“If it rains, we always take the umbrella. Tomorrow it will rain, so probably tomorrow we will take the umbrella.”

in the induction one.

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## Section 2 – Propositional logic

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### - 2 - Propositional logic.

At the core of Propositional Logic are atomic proposition, that are, any simple assertion. This means that, questions or meaningless sentences do not correspond to a proposition.

To build up more complex proposition we make use of connectives, that, up to a degree, have the same meaning to the English counterparts. Such connectives are:  $\neg$  (not) and  $\wedge$  (and). From these two, three additional connectives can be derived, though the latter are more a shorthand. Such additional connectives are:  $\vee$  (or), which is equivalent to  $\neg(\neg p \wedge \neg q)$ ,  $\implies$  (implies), equivalent to  $\neg p \vee q$  and  $\iff$  (if and only if), which corresponds to  $p \implies q \wedge q \implies p$ , where  $p$  and  $q$  are atomic propositions. We use the symbol **1** and **0**, to indicate, respectively, a true and a false statement.

#### - 2.1 - Validity, satisfiability and contradiction.

Let  $P = \{p_1, \dots, p_n\}$  be a set of atomic formulas, let  $\mathcal{F}(P)$  be the set of all formulas that can be derived from atomic propositions in  $P$ .

We say that a function  $A : P \rightarrow \{\mathbf{0}, \mathbf{1}\}$  is an assignment of  $P$ ; that is,  $A$  is an assignment of truth values to each atomic formula in  $P$ . The extension of  $A$  to  $\mathcal{F}(P)$  is immediate. Given  $F \in \mathcal{F}(P)$  and  $A$  an assignment of  $P$ , we say that  $A$  is a model of  $F$  if  $A(F) = \mathbf{1}$ ; we write  $A \models F$  to denote this concept. If  $A(F) = \mathbf{1}$  for all  $A$ , we say that  $F$  is a tautology; and we write  $\models F$  to denote it. Viceversa, if  $A(F) = \mathbf{0}$  for all  $A$ , we say that  $F$  is a contradiction. In this case we write  $\models \neg F$  to denote it. If  $A(F) = \mathbf{1}$  for some  $A$ , we say that  $F$  is satisfiable.

As the reader may be aware of, the satisfiability problem, i.e., the problem of establishing if a given formula is true, is NP-complete<sup>2</sup>.

#### - 2.2 - Consequence and equivalence.

Let  $F$  and  $G$  be two formulas; we say that  $G$  is a consequence of  $F$  if for every  $A$  such that  $A \models F$ , it holds  $A \models G$ . If it holds that  $F$  is a consequence of  $G$  and  $G$  a consequence of  $F$ , we say that  $F$  and  $G$  are equivalent; we write  $F \equiv G$  to denote this.

Let  $\mathcal{F} = \{F_1, F_2, \dots\}$  be a set of formulas. Given a formula  $G$ , can we determine if  $\mathcal{F} \models G$ ? Observe that if  $\mathcal{F}$  is finite, one could simply check whether

$$\bigwedge_{i=1}^n \mathcal{F} \implies G,$$

that is, if  $F_1 \wedge F_2 \wedge \dots \wedge F_n \implies G$ . In the case  $\mathcal{F}$  is infinite such approach

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<sup>2</sup>Throughout this notes we assume the reader to have a background in complexity theory.

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wont work at all. In this case we try to derive  $G$  from  $\mathcal{F}$ ; we denote this by  $\mathcal{F} \vdash G$ .

### - 2.3 - Rules, soundness and completeness of propositional logic.

Since Propositional Logic is, before everything, a logic it has rules which allows to deduce the truth of a sentence given another. Such rule system is a system of formal proof. In particular, we are interested in the relationship between the notion of formal proof and that of consequence; that is, we want our rule system to be *sound*.

**Definition (soundness and completeness)** Let  $P = \{p_1, p_2, \dots\}$  be a set of atomic propositions, and let  $\mathcal{F}(P)$ . We say that our rule system is sound if every formula derived from  $\mathcal{F}$  is a consequence of some proposition in  $\mathcal{F}$ . That is, if

$$\{G : \mathcal{F} \vdash G\} \subseteq \{G : \mathcal{F} \models G\}.$$

If it holds that

$$\{G : \mathcal{F} \models G\} \subseteq \{G : \mathcal{F} \vdash G\},$$

we say that our rule system is complete.

It can be shown that Propositional Logic is both sound and complete.

### - 2.4 - Horn formulas and resolution.

**Definition.** Let  $F$  be a formula. We say that  $F$  is a literal if it's either an atomic formula, or the negation of an atomic formula.

**Definition.** Let  $F$  be a formula. We say that  $F$  is in conjunctive normal form (CNF) if it can be written as conjunction of disjunctions. That is, if

$$F = \bigwedge_{i=1}^n \left( \bigvee_{j=1}^m L_{i,j} \right)$$

where  $L_{i,j}$  is a literal.

It easy to understand that not all formulas are given in CNF. Thankfully there exists an algorithm that allows one to convert each non-CNF formulas into the equivalent CNF. We illustrate such algorithm in the following.

Let  $F$  be a non-CNF formula, to get the equivalent CNF:

**Step 1:** Replace each subformula of the form  $G \implies H$  and  $G \iff H$  with their expanded counterparts. That is, replace each  $G \implies H$  with  $\neg G \vee H$  and all  $G \iff H$  with  $(\neg G \vee H) \wedge (\neg H \vee G)$ .

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**Step 2:** Get rid of all double negations and apply De Morgan's rules.  
That is, replace

$$\begin{aligned}\neg\neg G &\text{ with } G, \\ \neg(G \wedge H) &\text{ with } \neg G \vee \neg H, \text{ and} \\ \neg(G \vee H) &\text{ with } \neg G \wedge \neg H.\end{aligned}$$

**Step 3:** Distribute over  $\wedge$ . That is, given  $G \wedge (H \vee K)$  replace it with  $(G \wedge H) \vee (G \wedge K)$ .

If a formula  $F$  is in CNF and every disjunction has at most one positive literal, that is, all literals but one are negated, we say that  $F$  is a Horn formula. Among other things, Horn formulas admit a solution to the satisfiability problem.

### - 2.4.1 - Resolution.

Resolution is a theorem-proving technique based on refutation, i.e., we try to get a contradiction. To work properly, we have to write any given formula in a clause form, that is, we have to write the formula as disjunction of literals. Therefore, each disjunction in a CNF is a clause. To ease the notation we represent clauses as sets, where the clause  $\{\}$  means false.

#### Example

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Consider  $F = (\neg p \vee q) \wedge (q \vee r)$ , with our notation we write  $F$  as the set of sets  $\{\{\neg p, q\}, \{q, r\}\}$ .

But how do we proceed? Essentially, given a formula in clause form we repeatedly apply the *resolution rule*; i.e., given two clauses  $C_1 \cup \{A\}$  and  $C_2 \cup \{\neg A\}$  we get  $C_1 \cup C_2$ . That is, we look for pairs of clauses with two opposing literals and we merge them. We proceed this way until either we have no more clauses satisfying the above, or we get the empty clause, in which case we get the wanted contradiction.

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## Section 3 – Prepositional logic

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### - 3 - Prepositional logic.

We now discuss the concept of Prepositional Logic which, in its most general form, is at the core of the FOL introduced in *Section 1*.

In Prepositional Logic formulas are made up of predicates, as the name suggests; which are in turns made up of  $n$ -ary relations of terms<sup>3</sup>. Formally speaking, a term is either a constant  $a, b, c$ , a variable  $x, y, z$  or a  $n$ -ary function of terms. In the case of Propositional Logic, formulas were made up of atomic propositions held together by connectives; similarly, formulas in Propositional Logic are held together by connectives in addition to quantifiers  $\exists$  (exists) and  $\forall$  (for all), whose meaning is pretty clear. Additionally, the following equivalences hold.

$$\begin{aligned}\exists x (P(x) \vee Q(x)) &\equiv \exists x P(x) \vee \exists x Q(x) \\ \forall x (P(x) \wedge Q(x)) &\equiv \forall x P(x) \wedge \forall x Q(x)\end{aligned}$$

Let  $F$  be a formula of the form  $\forall x P(x)$ , where  $P(x)$  is some preposition; we say that  $x$  is a bound variable, i.e.,  $x$  is within the scope of a quantifier. Viceversa, we say that a variable  $x$  is free, or unbounded, if no quantifier is associated to it.

For what regards the complexity: in [2] *Gödel* proves that FOL is not decidable, while in [1] *Church* proves that it's semi-decidable.

We now introduce some definitions needed to understand the remainder of this section. Let  $F$  be a formula, we say that  $F$  is *closed* if it contains no free variable, we say it's *open* otherwise. A close formula is also called a *sentence*. For any given open formula one could consider the *universal closure* or the *existential closure*; in both case a quantifier is assigned to each free variable.

#### - 3.1 - Semantic interpretation in FOL.

So far we have discussed the syntactic aspect of FOL, but in doing so we made a semantic interpretation of the terms. To clearly untie semantic and syntax we have to introduce the concepts of *functional symbols* and *predicative symbols*, instead of functions and predicates respectively.

To define the semantic of a given formula we must fix a domain  $D$ , an interpretation function  $I : D^n \rightarrow D$  and an interpretation of the predicates. We define this way an interpretative structure. Similarly for what discussed about Propositional Logic, given close formula  $F$ , we call *model* for  $F$ , a interpretative structure that makes  $F$  true. Again, if  $F$  admits at least a model, we say that  $F$  is satisfiable, otherwise is unsatisfiable. We say that  $A$  is valid, if it's true for any interpretative structure.

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### Section 3 – Prepositional logic

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#### - 3.2 - Resolution in FOL.

In this section we show how the resolution algorithm presented in *Section 2.4.1* can be extended to formulas in FOL. As done in the case of Propositional Logic, we need to convert each formula into its clause form. But as we are about to show, this is not so straightforward.

The procedure we are about to show is not unique; apart from the last two steps, all other steps can be performed in any order. Since in general we deal with long formulas, we suggest as first step to remove any material condition, i.e., implications. Then move each negation inward, that is, replace each

$$\neg\forall x P(x) \text{ with } \exists x \neg P(x)$$

and

$$\neg\exists x P(x) \text{ with } \forall x \neg P(x).$$

As third step, if needed, to avoid confusion, standardize variable apart, meaning that, if the same variable is bounded to two, or more, quantifiers, one should introduce a new variables. For instance, take

$$\forall x \neg Q(x, z) \vee \exists x P(x),$$

here the second  $x$  can be replaced by the variable  $y$  to make more clear the distinction of the two parts; hence the formula becomes

$$\forall x \neg Q(x, z) \vee \exists y P(y).$$

As next step we introduce the prenex normal form (PNF), that is, a formula in the form

$$Q_1 x_1 Q_2 x_2 \cdots Q_n x_n P$$

where each  $Q_i$  is a quantifier and  $P$  is without quantifiers. For instance:  $\exists x \neg P(x) \vee \exists y Q(y)$  becomes  $\exists x \exists y \neg P(x) \vee Q(y)$ . We then transform the formula in PNF to its skolem normal form (SNF), i.e., we remove all existential quantifiers. More specifically, each quantifiers of the form  $\exists y$  is replaced by some functional symbol  $f(x_1, \dots, x_n)$  where each  $x_i$  is a universal quantified variable preceding  $y$ , or a constant if none. Lastly, we remove all universal quantifiers and assume the formula as universally quantified.

Note that formulas in SNF are not equivalent to the original ones; despite this, thaks to the following theorem and the fact that the resolution algorithm is refutation-complete, the problem does not exitst.

**Theorem (Skolem's theorem)** *A formula is unsatisfiable if and only if the SNF of its universal closure is unsatisfiable.*

Once the formula is in SNF the conversion to CNF and clause form is straightforward.



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## References.

- [1] A. Church. “A note on the Entscheidungsproblem”. In: *Journal of Symbolic Logic* 1.1 (1936), pp. 40–41. DOI: [10.2307/2269326](https://doi.org/10.2307/2269326).
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## **Acronyms.**

**CNF** conjunctive normal form. 6

**FOL** First Order Logic. 1

**KRR** Knowledge Representation and Reasoning. 1

**PNF** prenex normal form. 9

**SNF** skolem normal form. 9