

Parte I

Model Theory

Material on model theory is incomplete and experimental. It is currently simply an adaptation of Aldo Antonelli's notes on model theory, less those topics covered in the part on first-order logic (theories, completeness, compactness). It requires much more introduction, motivation, and explanation, as well as exercises, to be useful for a textbook. Andy Arana is at planning to work on this part specifically (issue #65).

Capítulo 1

Basics of Model Theory

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1.1 Reducts and Expansions

Often it is useful or necessary to compare languages which have symbols in common, as well as *estruturas* for these languages. The most common case is when all the symbols in a *linguagem* $\mathcal{L}$ are also part of a *linguagem* $\mathcal{L}'$, O.s., $\mathcal{L} \subseteq \mathcal{L}'$. An $\mathcal{L}$ -*estrutura* $\mathfrak{M}$ can then always be expanded to an $\mathcal{L}'$ -*estrutura* by adding interpretations of the additional symbols while leaving the interpretations of the common symbols the same. On the other hand, from an $\mathcal{L}'$ -structure $\mathfrak{M}'$ we can obtain an $\mathcal{L}$ -structure simply by “forgetting” the interpretations of the symbols that do not occur in $\mathcal{L}$.

mod:bas:red: defn:red **Definição 1.1.** Suppose $\mathcal{L} \subseteq \mathcal{L}'$, $\mathfrak{M}$ is an $\mathcal{L}$ -*estrutura* and $\mathfrak{M}'$ is an $\mathcal{L}'$ -*estrutura*. $\mathfrak{M}$ is the *reduct* of $\mathfrak{M}'$ to $\mathcal{L}$, and $\mathfrak{M}'$ is an *expansion* of $\mathfrak{M}$ to $\mathcal{L}'$ iff

1. $|\mathfrak{M}| = |\mathfrak{M}'|$
2. For every *símbolo de constante* $c \in \mathcal{L}$, $c^{\mathfrak{M}} = c^{\mathfrak{M}'}$.
3. For every *símbolo de função* $f \in \mathcal{L}$, $f^{\mathfrak{M}} = f^{\mathfrak{M}'}$.
4. For every *símbolo de predicado* $P \in \mathcal{L}$, $P^{\mathfrak{M}} = P^{\mathfrak{M}'}$.

mod:bas:red: prop:red **Proposição 1.2.** If an $\mathcal{L}$ -*estrutura* $\mathfrak{M}$ is a reduct of an $\mathcal{L}'$ -*estrutura* $\mathfrak{M}'$, then for all $\mathcal{L}$ -*sentenças* φ ,

$$\mathfrak{M} \models \varphi \text{ iff } \mathfrak{M}' \models \varphi.$$

Prova. Exercise. □

Problema 1.1. Prove *Proposição 1.2*.

Definição 1.3. When we have an $\mathcal{L}$ -structure $\mathfrak{M}$, and $\mathcal{L}' = \mathcal{L} \cup \{P\}$ is the expansion of $\mathcal{L}$ obtained by adding a single n -place **símbolo de predicado** P , and $R \subseteq |\mathfrak{M}|^n$ is an n -place relation, then we write $(\mathfrak{M}, R)$ for the expansion $\mathfrak{M}'$ of $\mathfrak{M}$ with $P^{\mathfrak{M}'} = R$.

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1.2 Subestruturas

The **domínio** of a **estrutura** $\mathfrak{M}$ may be a subset of another $\mathfrak{M}'$. But we should obviously only consider $\mathfrak{M}$ a “part” of $\mathfrak{M}'$ if not only $|\mathfrak{M}| \subseteq |\mathfrak{M}'|$, but $\mathfrak{M}$ and $\mathfrak{M}'$ “agree” in how they interpret the symbols of the language at least on the shared part $|\mathfrak{M}|$.

mod:bas:sub:
sec

Definição 1.4. Given **estruturas** $\mathfrak{M}$ and $\mathfrak{M}'$ for the same language $\mathcal{L}$, we say that $\mathfrak{M}$ is a **subestrutura** of $\mathfrak{M}'$, and $\mathfrak{M}'$ an *extension* of $\mathfrak{M}$, written $\mathfrak{M} \subseteq \mathfrak{M}'$, iff

mod:bas:sub:
defn:substructure

1. $|\mathfrak{M}| \subseteq |\mathfrak{M}'|$,
2. For each constant $c \in \mathcal{L}$, $c^{\mathfrak{M}} = c^{\mathfrak{M}'}$;
3. For each n -place **símbolo de função** $f \in \mathcal{L}$ $f^{\mathfrak{M}}(a_1, \dots, a_n) = f^{\mathfrak{M}'}(a_1, \dots, a_n)$ for all $a_1, \dots, a_n \in |\mathfrak{M}|$.
4. For each n -place **símbolo de predicado** $R \in \mathcal{L}$, $\langle a_1, \dots, a_n \rangle \in R^{\mathfrak{M}}$ iff $\langle a_1, \dots, a_n \rangle \in R^{\mathfrak{M}'}$ for all $a_1, \dots, a_n \in |\mathfrak{M}|$.

Observação 1. If the language contains no constant or **símbolos de função**, then any $N \subseteq |\mathfrak{M}|$ determines a **subestrutura** $\mathfrak{N}$ of $\mathfrak{M}$ with **domínio** $|\mathfrak{N}| = N$ by putting $R^{\mathfrak{N}} = R^{\mathfrak{M}} \cap N^n$.

mod:bas:sub:
rem:substructure

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1.3 Overspill

Teorema 1.5. If a set Γ of sentences has arbitrarily large finite models, then it has an infinite model.

mod:bas:ove:
sec
mod:bas:ove:
overspill

Prova. Expand the language of Γ by adding countably many new constants $c_0, c_1, \dots$ and consider the set $\Gamma \cup \{c_i \neq c_j : i \neq j\}$. To say that Γ has arbitrarily large finite models means that for every $m > 0$ there is $n \geq m$ such that Γ has a model of cardinality n . This implies that $\Gamma \cup \{c_i \neq c_j : i \neq j\}$ is finitely satisfiable. By compactness, $\Gamma \cup \{c_i \neq c_j : i \neq j\}$ has a model $\mathfrak{M}$ whose domain must be infinite, since it satisfies all inequalities $c_i \neq c_j$. $\square$

mod:bas:ove:
inf-not-fo

Proposição 1.6. *There is no sentence φ of any first-order language that is true in a estrutura $\mathfrak{M}$ if and only if the domain $|\mathfrak{M}|$ of the estrutura is infinite.*

Prova. If there were such a φ , its negation $\neg\varphi$ would be true in all and only the finite estruturas, and it would therefore have arbitrarily large finite models but it would lack an infinite model, contradicting Teorema 1.5. $\square$

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1.4 Isomorphic Structures

mod:bas:iso:
sec

First-order estruturas can be alike in one of two ways. One way in which they can be alike is that they make the same sentenças true. We call such estruturas *elementarily equivalent*. But structures can be very different and still make the same sentenças true—for instance, one can be enumerável and the other not. This is because there are lots of features of a estrutura that cannot be expressed in first-order languages, either because the language is not rich enough, or because of fundamental limitations of first-order logic such as the Löwenheim–Skolem theorem. So another, stricter, aspect in which estruturas can be alike is if they are fundamentally the same, in the sense that they only differ in the objects that make them up, but not in their structural features. A way of making this precise is by the notion of an *isomorphism*.

mod:bas:iso:
defn:elem-equiv

Definição 1.7. Given two estruturas $\mathfrak{M}$ and $\mathfrak{M}'$ for the same linguagem $\mathcal{L}$, we say that $\mathfrak{M}$ is *elementarily equivalent* to $\mathfrak{M}'$, written $\mathfrak{M} \equiv \mathfrak{M}'$, if and only if for every sentença φ of $\mathcal{L}$, $\mathfrak{M} \models \varphi$ iff $\mathfrak{M}' \models \varphi$.

mod:bas:iso:
defn:isomorphism

Definição 1.8. Given two estruturas $\mathfrak{M}$ and $\mathfrak{M}'$ for the same linguagem $\mathcal{L}$, we say that $\mathfrak{M}$ is *isomorphic* to $\mathfrak{M}'$, written $\mathfrak{M} \simeq \mathfrak{M}'$, if and only if there is a function $h: |\mathfrak{M}| \rightarrow |\mathfrak{M}'|$ such that:

1. h is **injetiva**: if $h(x) = h(y)$ then $x = y$;
2. h is **sobrejetiva**: for every $y \in |\mathfrak{M}'|$ there is $x \in |\mathfrak{M}|$ such that $h(x) = y$;
3. for every **símbolo de constante** c : $h(c^{\mathfrak{M}}) = c^{\mathfrak{M}'}$;
4. for every n -place **símbolo de predicado** P :

mod:bas:iso:
defn:iso-const
mod:bas:iso:
defn:iso-pred

$$\langle a_1, \dots, a_n \rangle \in P^{\mathfrak{M}} \quad \text{iff} \quad \langle h(a_1), \dots, h(a_n) \rangle \in P^{\mathfrak{M}'};$$

mod:bas:iso:
defn:iso-func

5. for every n -place **símbolo de função** f :

$$h(f^{\mathfrak{M}}(a_1, \dots, a_n)) = f^{\mathfrak{M}'}(h(a_1), \dots, h(a_n)).$$

mod:bas:iso:
thm:isom

Teorema 1.9. *If $\mathfrak{M} \simeq \mathfrak{M}'$ then $\mathfrak{M} \equiv \mathfrak{M}'$.*

Prova. Let h be an isomorphism of $\mathfrak{M}$ onto $\mathfrak{M}'$. For any assignment s , $h \circ s$ is the composition of h and s , O.s., the assignment in $\mathfrak{M}'$ such that $(h \circ s)(x) = h(s(x))$. By induction on t and φ one can prove the stronger claims:

- a. $h(\text{Val}_s^{\mathfrak{M}}(t)) = \text{Val}_{h \circ s}^{\mathfrak{M}'}(t)$.
- b. $\mathfrak{M}, s \models \varphi$ iff $\mathfrak{M}', h \circ s \models \varphi$.

The first is proved by induction on the complexity of t .

1. If $t \equiv c$, then $\text{Val}_s^{\mathfrak{M}}(c) = c^{\mathfrak{M}}$ and $\text{Val}_{h \circ s}^{\mathfrak{M}'}(c) = c^{\mathfrak{M}'}$. Thus, $h(\text{Val}_s^{\mathfrak{M}}(t)) = h(c^{\mathfrak{M}}) = c^{\mathfrak{M}'}$ (by (3) of Definição 1.8) $= \text{Val}_{h \circ s}^{\mathfrak{M}'}(t)$.
2. If $t \equiv x$, then $\text{Val}_s^{\mathfrak{M}}(x) = s(x)$ and $\text{Val}_{h \circ s}^{\mathfrak{M}'}(x) = h(s(x))$. Thus, $h(\text{Val}_s^{\mathfrak{M}}(x)) = h(s(x)) = \text{Val}_{h \circ s}^{\mathfrak{M}'}(x)$.
3. If $t \equiv f(t_1, \dots, t_n)$, then

$$\begin{aligned} \text{Val}_s^{\mathfrak{M}}(t) &= f^{\mathfrak{M}}(\text{Val}_s^{\mathfrak{M}}(t_1), \dots, \text{Val}_s^{\mathfrak{M}}(t_n)) \quad \text{and} \\ \text{Val}_{h \circ s}^{\mathfrak{M}'}(t) &= f^{\mathfrak{M}'}(\text{Val}_{h \circ s}^{\mathfrak{M}'}(t_1), \dots, \text{Val}_{h \circ s}^{\mathfrak{M}'}(t_n)). \end{aligned}$$

The induction hypothesis is that for each i , $h(\text{Val}_s^{\mathfrak{M}}(t_i)) = \text{Val}_{h \circ s}^{\mathfrak{M}'}(t_i)$. So,

$$\begin{aligned} h(\text{Val}_s^{\mathfrak{M}}(t)) &= h(f^{\mathfrak{M}}(\text{Val}_s^{\mathfrak{M}}(t_1), \dots, \text{Val}_s^{\mathfrak{M}}(t_n))) \\ &= f^{\mathfrak{M}'}(h(\text{Val}_s^{\mathfrak{M}}(t_1)), \dots, h(\text{Val}_s^{\mathfrak{M}}(t_n))) \quad (1.1) \quad \text{mod:bas:iso:iso-1} \\ &= f^{\mathfrak{M}'}(\text{Val}_{h \circ s}^{\mathfrak{M}'}(t_1), \dots, \text{Val}_{h \circ s}^{\mathfrak{M}'}(t_n)) \quad (1.2) \quad \text{mod:bas:iso:iso-2} \\ &= \text{Val}_{h \circ s}^{\mathfrak{M}'}(t) \end{aligned}$$

Here, Eq. (1.1) follows by (5) of Definição 1.8 and Eq. (1.2) by induction hypothesis.

Part (b) is left as an exercise.

If φ is a sentence, the assignments s and $h \circ s$ are irrelevant, and we have $\mathfrak{M} \models \varphi$ iff $\mathfrak{M}' \models \varphi$. $\square$

Problema 1.2. Carry out the proof of (b) of Teorema 1.9 in detail. Make sure to note where each of the five properties characterizing isomorphisms of Definição 1.8 is used.

Definição 1.10. An *automorphism* of a structure $\mathfrak{M}$ is an isomorphism of $\mathfrak{M}$ onto itself.

Problema 1.3. Show that for any structure $\mathfrak{M}$, if X is a definable subset of $\mathfrak{M}$, and h is an automorphism of $\mathfrak{M}$, then $X = \{h(x) : x \in X\}$ (O.s., X is fixed under h).

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1.5 The Theory of a Estrutura

Every estrutura $\mathfrak{M}$ makes some sentenças true, and some false. The set of all the sentenças it makes true is called its *theory*. That set is in fact a theory, since anything it entails must be true in all its models, including $\mathfrak{M}$.

Definição 1.11. Given a estrutura $\mathfrak{M}$, the *theory* of $\mathfrak{M}$ is the set $\text{Th}(\mathfrak{M})$ of sentenças that are true in $\mathfrak{M}$, O.s., $\text{Th}(\mathfrak{M}) = \{\varphi : \mathfrak{M} \models \varphi\}$.

We also use the term “theory” informally to refer to sets of sentenças having an intended interpretation, whether deductively closed or not.

Proposição 1.12. For any $\mathfrak{M}$, $\text{Th}(\mathfrak{M})$ is complete.

Prova. For any sentença φ either $\mathfrak{M} \models \varphi$ or $\mathfrak{M} \models \neg\varphi$, so either $\varphi \in \text{Th}(\mathfrak{M})$ or $\neg\varphi \in \text{Th}(\mathfrak{M})$. $\square$

mod:bas:thm: prop:equiv **Proposição 1.13.** If $\mathfrak{N} \models \varphi$ for every $\varphi \in \text{Th}(\mathfrak{M})$, then $\mathfrak{M} \equiv \mathfrak{N}$.

Prova. Since $\mathfrak{N} \models \varphi$ for all $\varphi \in \text{Th}(\mathfrak{M})$, $\text{Th}(\mathfrak{M}) \subseteq \text{Th}(\mathfrak{N})$. If $\mathfrak{N} \models \varphi$, then $\mathfrak{N} \not\models \neg\varphi$, so $\neg\varphi \notin \text{Th}(\mathfrak{M})$. Since $\text{Th}(\mathfrak{M})$ is complete, $\varphi \in \text{Th}(\mathfrak{M})$. So, $\text{Th}(\mathfrak{N}) \subseteq \text{Th}(\mathfrak{M})$, and we have $\mathfrak{M} \equiv \mathfrak{N}$. $\square$

mod:bas:thm: remark:R *Observação 2.* Consider $\mathfrak{R} = \langle \mathbb{R}, < \rangle$, the estrutura whose domain is the set $\mathbb{R}$ of the real numbers, in the linguagem comprising only a 2-place símbolo de predicado interpreted as the $<$ relation over the reals. Clearly $\mathfrak{R}$ is não enumerável; however, since $\text{Th}(\mathfrak{R})$ is obviously consistent, by the Löwenheim–Skolem theorem it has a enumerável model, say $\mathfrak{S}$, and by **Proposição 1.13**, $\mathfrak{R} \equiv \mathfrak{S}$. Moreover, since $\mathfrak{R}$ and $\mathfrak{S}$ are not isomorphic, this shows that the converse of **Teorema 1.9** fails in general.

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1.6 Partial Isomorphisms

Definição 1.14. Given two estruturas $\mathfrak{M}$ and $\mathfrak{N}$, a *partial isomorphism* from $\mathfrak{M}$ to $\mathfrak{N}$ is a finite partial function p taking arguments in $|\mathfrak{M}|$ and returning values in $|\mathfrak{N}|$, which satisfies the isomorphism conditions from **Definição 1.8** on its domain:

1. p is injetiva;
2. for every símbolo de constante c : if $p(c^{\mathfrak{M}})$ is defined, then $p(c^{\mathfrak{M}}) = c^{\mathfrak{N}}$;
3. for every n -place símbolo de predicado P : if $a_1, \dots, a_n$ are in the domain of p , then $\langle a_1, \dots, a_n \rangle \in P^{\mathfrak{M}}$ if and only if $\langle p(a_1), \dots, p(a_n) \rangle \in P^{\mathfrak{N}}$;
4. for every n -place símbolo de função f : if $a_1, \dots, a_n$ are in the domain of p , then $p(f^{\mathfrak{M}}(a_1, \dots, a_n)) = f^{\mathfrak{N}}(p(a_1), \dots, p(a_n))$.

That p is finite means that $\text{dom}(p)$ is finite.

Notice that the empty function $\emptyset$ is always a partial isomorphism between any two **estruturas**.

Definição 1.15. Two **estruturas** $\mathfrak{M}$ and $\mathfrak{N}$, are *partially isomorphic*, written $\mathfrak{M} \simeq_p \mathfrak{N}$, if and only if there is a non-empty set I of partial isomorphisms between $\mathfrak{M}$ and $\mathfrak{N}$ satisfying the *back-and-forth* property: mod:bas:pis:
defn:partialisom

1. (*Forth*) For every $p \in I$ and $a \in |\mathfrak{M}|$ there is $q \in I$ such that $p \subseteq q$ and a is in the domain of q ;
2. (*Back*) For every $p \in I$ and $b \in |\mathfrak{N}|$ there is $q \in I$ such that $p \subseteq q$ and b is in the range of q .

Teorema 1.16. If $\mathfrak{M} \simeq_p \mathfrak{N}$ and $\mathfrak{M}$ and $\mathfrak{N}$ are **enumerável**, then $\mathfrak{M} \simeq \mathfrak{N}$. mod:bas:pis:
thm:p-isom1

Prova. Since $\mathfrak{M}$ and $\mathfrak{N}$ are **enumerável**, let $|\mathfrak{M}| = \{a_0, a_1, \dots\}$ and $|\mathfrak{N}| = \{b_0, b_1, \dots\}$. Starting with an arbitrary $p_0 \in I$, we define an increasing sequence of partial isomorphisms $p_0 \subseteq p_1 \subseteq p_2 \subseteq \dots$ as follows:

1. if $n + 1$ is odd, say $n = 2r$, then using the Forth property find a $p_{n+1} \in I$ such that $p_n \subseteq p_{n+1}$ and a_r is in the domain of p_{n+1} ;
2. if $n + 1$ is even, say $n + 1 = 2r$, then using the Back property find a $p_{n+1} \in I$ such that $p_n \subseteq p_{n+1}$ and b_r is in the range of p_{n+1} .

If we now put:

$$p = \bigcup_{n \geq 0} p_n,$$

we have that p is a an isomorphism between $\mathfrak{M}$ and $\mathfrak{N}$. □

Problema 1.4. Show in detail that p as defined in **Teorema 1.16** is in fact an isomorphism.

Teorema 1.17. Suppose $\mathfrak{M}$ and $\mathfrak{N}$ are **estruturas** for a purely relational **linguagem** (a **linguagem** containing only **símbolos de predicado**, and no **símbolos de função** or constants). Then if $\mathfrak{M} \simeq_p \mathfrak{N}$, also $\mathfrak{M} \equiv \mathfrak{N}$. mod:bas:pis:
thm:p-isom2

Prova. By induction on **fórmulas**, one shows that if $a_1, \dots, a_n$ and $b_1, \dots, b_n$ are such that there is a partial isomorphism p mapping each a_i to b_i and $s_1(x_i) = a_i$ and $s_2(x_i) = b_i$ (for $i = 1, \dots, n$), then $\mathfrak{M}, s_1 \models \varphi$ if and only if $\mathfrak{N}, s_2 \models \varphi$. The case for $n = 0$ gives $\mathfrak{M} \equiv \mathfrak{N}$. □

Observação 3. If **símbolos de função** are present, the previous result is still true, but one needs to consider the isomorphism induced by p between the sub**estrutura** of $\mathfrak{M}$ generated by $a_1, \dots, a_n$ and the sub**estrutura** of $\mathfrak{N}$ generated by $b_1, \dots, b_n$.

The previous result can be “broken down” into stages by establishing a connection between the number of nested quantifiers in a **fórmula** and how many times the relevant partial isomorphisms can be extended.

Definição 1.18. For any **fórmula** φ , the *quantifier rank* of φ , denoted by $\text{qr}(\varphi) \in \mathbb{N}$, is recursively defined as the highest number of nested quantifiers in φ . Two **estruturas** $\mathfrak{M}$ and $\mathfrak{N}$ are *n-equivalent*, written $\mathfrak{M} \equiv_n \mathfrak{N}$, if they agree on all sentences of quantifier rank less than or equal to n .

*mod:bas:pis:
prop:qr-finite*

Proposição 1.19. Let $\mathcal{L}$ be a finite purely relational **linguagem**, O.s., a **linguagem** containing finitely many **símbolos de predicado** and **símbolos de constante**, and no **símbolos de função**. Then for each $n \in \mathbb{N}$ there are only finitely many first-order **sentenças** in the **linguagem** $\mathcal{L}$ that have quantifier rank no greater than n , up to logical equivalence.

Prova. By induction on n . □

Definição 1.20. Given a **estrutura** $\mathfrak{M}$, let $|\mathfrak{M}|^{<\omega}$ be the set of all finite sequences over $|\mathfrak{M}|$. We use $\mathbf{a}, \mathbf{b}, \mathbf{c}, \dots$ to range over finite sequences of elements. If $\mathbf{a} \in |\mathfrak{M}|^{<\omega}$ and $a \in |\mathfrak{M}|$, then $\mathbf{a}a$ represents the *concatenation* of $\mathbf{a}$ with a .

Definição 1.21. Given **estruturas** $\mathfrak{M}$ and $\mathfrak{N}$, we define relations $I_n \subseteq |\mathfrak{M}|^{<\omega} \times |\mathfrak{N}|^{<\omega}$ between sequences of equal length, by recursion on n as follows:

1. $I_0(\mathbf{a}, \mathbf{b})$ if and only if $\mathbf{a}$ and $\mathbf{b}$ satisfy the same atomic **fórmulas** in $\mathfrak{M}$ and $\mathfrak{N}$; O.s., if $s_1(x_i) = a_i$ and $s_2(x_i) = b_i$ and φ is atomic with all **variáveis** among $x_1, \dots, x_n$, then $\mathfrak{M}, s_1 \models \varphi$ if and only if $\mathfrak{N}, s_2 \models \varphi$.
2. $I_{n+1}(\mathbf{a}, \mathbf{b})$ if and only if for every $a \in |\mathfrak{M}|$ there is a $b \in |\mathfrak{N}|$ such that $I_n(\mathbf{a}a, \mathbf{b}b)$, and vice-versa.

Definição 1.22. Write $\mathfrak{M} \approx_n \mathfrak{N}$ if $I_n(\Lambda, \Lambda)$ holds of $\mathfrak{M}$ and $\mathfrak{N}$ (where Λ is the empty sequence).

*mod:bas:pis:
thm:b-n-f*

Teorema 1.23. Let $\mathcal{L}$ be a purely relational **linguagem**. Then $I_n(\mathbf{a}, \mathbf{b})$ implies that for every φ such that $\text{qr}(\varphi) \leq n$, we have $\mathfrak{M}, \mathbf{a} \models \varphi$ if and only if $\mathfrak{N}, \mathbf{b} \models \varphi$ (where again $\mathbf{a}$ satisfies φ if any s such that $s(x_i) = a_i$ satisfies φ). Moreover, if $\mathcal{L}$ is finite, the converse also holds.

Prova. The proof that $I_n(\mathbf{a}, \mathbf{b})$ implies that $\mathbf{a}$ and $\mathbf{b}$ satisfy the same **fórmulas** of quantifier rank no greater than n is by an easy induction on φ . For the converse we proceed by induction on n , using **Proposição 1.19**, which ensures that for each n there are at most finitely many non-equivalent **fórmulas** of that quantifier rank.

For $n = 0$ the hypothesis that $\mathbf{a}$ and $\mathbf{b}$ satisfy the same quantifier-free **fórmulas** gives that they satisfy the same atomic ones, so that $I_0(\mathbf{a}, \mathbf{b})$.

For the $n + 1$ case, suppose that $\mathbf{a}$ and $\mathbf{b}$ satisfy the same **fórmulas** of quantifier rank no greater than $n + 1$; in order to show that $I_{n+1}(\mathbf{a}, \mathbf{b})$ suffices

to show that for each $a \in |\mathfrak{M}|$ there is a $b \in |\mathfrak{N}|$ such that $I_n(\mathbf{a}a, \mathbf{b}b)$, and by the inductive hypothesis again suffices to show that for each $a \in |\mathfrak{M}|$ there is a $b \in |\mathfrak{N}|$ such that $\mathbf{a}a$ and $\mathbf{b}b$ satisfy the same **fórmulas** of quantifier rank no greater than n .

Given $a \in |\mathfrak{M}|$, let τ_n^a be set of **fórmulas** $\psi(x, \mathbf{y})$ of rank no greater than n satisfied by $\mathbf{a}a$ in $\mathfrak{M}$; τ_n^a is finite, so we can assume it is a single first-order **fórmula**. It follows that $\mathbf{a}$ satisfies $\exists x \tau_n^a(x, \mathbf{y})$, which has quantifier rank no greater than $n + 1$. By hypothesis $\mathbf{b}$ satisfies the same **fórmula** in $\mathfrak{N}$, so that there is a $b \in |\mathfrak{N}|$ such that $\mathbf{b}b$ satisfies τ_n^a ; in particular, $\mathbf{b}b$ satisfies the same **fórmulas** of quantifier rank no greater than n as $\mathbf{a}a$. Similarly one shows that for every $b \in |\mathfrak{N}|$ there is $a \in |\mathfrak{M}|$ such that $\mathbf{a}a$ and $\mathbf{b}b$ satisfy the same **fórmulas** of quantifier rank no greater than n , which completes the proof. $\square$

Corolário 1.24. *If $\mathfrak{M}$ and $\mathfrak{N}$ are purely relational **estruturas** in a finite **linguagem**, then $\mathfrak{M} \approx_n \mathfrak{N}$ if and only if $\mathfrak{M} \equiv_n \mathfrak{N}$. In particular $\mathfrak{M} \equiv \mathfrak{N}$ if and only if for each n , $\mathfrak{M} \approx_n \mathfrak{N}$.* mod:bas:pis:
cor:b-n-f

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1.7 Dense Linear Orders

Definição 1.25. A *dense linear ordering without endpoints* is a **estrutura** $\mathfrak{M}$ for the **linguagem** containing a single 2-place **símbolo de predicado** $<$ satisfying the following sentences:

1. $\forall x \neg x < x$;
2. $\forall x \forall y \forall z (x < y \rightarrow (y < z \rightarrow x < z))$;
3. $\forall x \forall y (x < y \vee x = y \vee y < x)$;
4. $\forall x \exists y x < y$;
5. $\forall x \exists y y < x$;
6. $\forall x \forall y (x < y \rightarrow \exists z (x < z \wedge z < y))$.

Teorema 1.26. *Any two **enumerável** dense linear orderings without endpoints are isomorphic.* mod:bas:dlo:
thm:cantorQ

Prova. Let $\mathfrak{M}_1$ and $\mathfrak{M}_2$ be **enumerável** dense linear orderings without endpoints, with $<_1 = <^{\mathfrak{M}_1}$ and $<_2 = <^{\mathfrak{M}_2}$, and let $\mathcal{I}$ be the set of all partial isomorphisms between them. $\mathcal{I}$ is not empty since at least $\emptyset \in \mathcal{I}$. We show that $\mathcal{I}$ satisfies the Back-and-Forth property. Then $\mathfrak{M}_1 \simeq_p \mathfrak{M}_2$, and the theorem follows by **Teorema 1.16**.

To show $\mathcal{I}$ satisfies the Forth property, let $p \in \mathcal{I}$ and let $p(a_i) = b_i$ for $i = 1, \dots, n$, and without loss of generality suppose $a_1 <_1 a_2 <_1 \dots <_1 a_n$. Given $a \in |\mathfrak{M}_1|$, find $b \in |\mathfrak{M}_2|$ as follows:

1. if $a <_1 a_1$ let $b \in |\mathfrak{M}_2|$ be such that $b <_2 b_1$;
2. if $a_n <_1 a$ let $b \in |\mathfrak{M}_2|$ be such that $b_n <_2 b$;
3. if $a_i <_1 a <_1 a_{i+1}$ for some i , then let $b \in |\mathfrak{M}_2|$ be such that $b_i <_2 b <_2 b_{i+1}$.

It is always possible to find a b with the desired property since $\mathfrak{M}_2$ is a dense linear ordering without endpoints. Define $q = p \cup \{(a, b)\}$ so that $q \in \mathcal{I}$ is the desired extension of p . This establishes the Forth property. The Back property is similar. So $\mathfrak{M}_1 \simeq_p \mathfrak{M}_2$; by [Teorema 1.16](#), $\mathfrak{M}_1 \simeq \mathfrak{M}_2$. $\square$

Problema 1.5. Complete the proof of [Teorema 1.26](#) by verifying that $\mathcal{I}$ satisfies the Back property.

Observação 4. Let $\mathfrak{S}$ be any [enumerável](#) dense linear ordering without endpoints. Then (by [Teorema 1.26](#)) $\mathfrak{S} \simeq \mathfrak{Q}$, where $\mathfrak{Q} = (\mathbb{Q}, <)$ is the [enumerável](#) dense linear ordering having the set $\mathbb{Q}$ of the rational numbers as its domain. Now consider again the [estrutura](#) $\mathfrak{R} = (\mathbb{R}, <)$ from [Observação 2](#). We saw that there is a [enumerável estrutura](#) $\mathfrak{S}$ such that $\mathfrak{R} \equiv \mathfrak{S}$. But $\mathfrak{S}$ is a [enumerável](#) dense linear ordering without endpoints, and so it is isomorphic (and hence elementarily equivalent) to the [estrutura](#) $\mathfrak{Q}$. By transitivity of elementary equivalence, $\mathfrak{R} \equiv \mathfrak{Q}$. (We could have shown this directly by establishing $\mathfrak{R} \simeq_p \mathfrak{Q}$ by the same back-and-forth argument.)

Capítulo 2

Models of Arithmetic

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2.1 Introduction

The *standard model* of arithmetic is the **estrutura** $\mathfrak{N}$ with $|\mathfrak{N}| = \mathbb{N}$ in which $\mathbf{o}$, $\mathbf{!}$, $+$, $\times$, and $<$ are interpreted as you would expect. That is, $\mathbf{o}$ is 0, $\mathbf{!}$ is the successor function, $+$ is interpreted as addition and $\times$ as multiplication of the numbers in $\mathbb{N}$. Specifically,

$$\begin{aligned}\mathbf{o}^{\mathfrak{N}} &= 0 \\ \mathbf{!}^{\mathfrak{N}}(n) &= n + 1 \\ +^{\mathfrak{N}}(n, m) &= n + m \\ \times^{\mathfrak{N}}(n, m) &= nm\end{aligned}$$

Of course, there are structures for $\mathcal{L}_A$ that have domains other than $\mathbb{N}$. For instance, we can take $\mathfrak{M}$ with domain $|\mathfrak{M}| = \{a\}^*$ (the finite sequences of the single symbol a , O.s., $\emptyset$, a , aa , aaa , $\dots$), and interpretations

$$\begin{aligned}\mathbf{o}^{\mathfrak{M}} &= \emptyset \\ \mathbf{!}^{\mathfrak{M}}(s) &= s \frown a \\ +^{\mathfrak{M}}(n, m) &= a^{n+m} \\ \times^{\mathfrak{M}}(n, m) &= a^{nm}\end{aligned}$$

These two structures are “essentially the same” in the sense that the only difference is the **membros** of the **domínios** but not how the **membros** of the **domínios** are related among each other by the interpretation functions. We say that the two **estruturas** are *isomorphic*.

It is an easy consequence of the compactness theorem that any theory true in $\mathfrak{N}$ also has models that are not isomorphic to $\mathfrak{N}$. Such structures are called *non-standard*. The interesting thing about them is that while the **membros** of a

standard model (O.s., $\mathfrak{N}$, but also all **estruturas** isomorphic to it) are exhausted by the values of the standard numerals $\bar{n}$, O.s.,

$$|\mathfrak{N}| = \{\text{Val}^{\mathfrak{N}}(\bar{n}) : n \in \mathbb{N}\}$$

that isn't the case in non-standard models: if $\mathfrak{M}$ is non-standard, then there is at least one $x \in |\mathfrak{M}|$ such that $x \neq \text{Val}^{\mathfrak{M}}(\bar{n})$ for all n .

These non-standard elements are pretty neat: they are “infinite natural numbers.” But their existence also explains, in a sense, the incompleteness phenomena. Consider an example, p.ex., the consistency statement for Peano arithmetic, $\text{Con}_{\mathbf{PA}}$, O.s., $\neg \exists x \text{Prf}_{\mathbf{PA}}(x, \ulcorner \perp \urcorner)$. Since $\mathbf{PA}$ neither proves $\text{Con}_{\mathbf{PA}}$ nor $\neg \text{Con}_{\mathbf{PA}}$, either can be consistently added to $\mathbf{PA}$. Since $\mathbf{PA}$ is consistent, $\mathfrak{N} \models \text{Con}_{\mathbf{PA}}$, and consequently $\mathfrak{N} \not\models \neg \text{Con}_{\mathbf{PA}}$. So $\mathfrak{N}$ is *not* a model of $\mathbf{PA} \cup \{\neg \text{Con}_{\mathbf{PA}}\}$, and all its models must be nonstandard. Models of $\mathbf{PA} \cup \{\neg \text{Con}_{\mathbf{PA}}\}$ must contain some **membro** that serves as the witness that makes $\exists x \text{Prf}_{\mathbf{PA}}(\ulcorner \perp \urcorner)$ true, O.s., a Gödel number of a **derivação** of a contradiction from $\mathbf{PA}$. Such **um membro** can't be standard—since $\mathbf{PA} \vdash \neg \text{Prf}_{\mathbf{PA}}(\bar{n}, \ulcorner \perp \urcorner)$ for every n .

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2.2 Standard Models of Arithmetic

mod:mar:stm:
sec

The language of arithmetic $\mathcal{L}_A$ is obviously intended to be about numbers, specifically, about natural numbers. So, “the” standard model $\mathfrak{N}$ is special: it is the model we want to talk about. But in logic, we are often just interested in structural properties, and any two **estruturas** that are isomorphic share those. So we can be a bit more liberal, and consider any **estrutura** that is isomorphic to $\mathfrak{N}$ “standard.”

Definição 2.1. A **estrutura** for $\mathcal{L}_A$ is *standard* if it is isomorphic to $\mathfrak{N}$.

mod:mar:stm:
prop:standard-domain

Proposição 2.2. If a **estrutura** $\mathfrak{M}$ is standard, then its domain is the set of values of the standard numerals, O.s.,

$$|\mathfrak{M}| = \{\text{Val}^{\mathfrak{M}}(\bar{n}) : n \in \mathbb{N}\}$$

Prova. Clearly, every $\text{Val}^{\mathfrak{M}}(\bar{n}) \in |\mathfrak{M}|$. We just have to show that every $x \in |\mathfrak{M}|$ is equal to $\text{Val}^{\mathfrak{M}}(\bar{n})$ for some n . Since $\mathfrak{M}$ is standard, it is isomorphic to $\mathfrak{N}$. Suppose $g: \mathbb{N} \rightarrow |\mathfrak{M}|$ is an isomorphism. Then $g(n) = g(\text{Val}^{\mathfrak{N}}(\bar{n})) = \text{Val}^{\mathfrak{M}}(\bar{n})$. But for every $x \in |\mathfrak{M}|$, there is an $n \in \mathbb{N}$ such that $g(n) = x$, since g is **sobrejetiva**. $\square$

If a structure $\mathfrak{M}$ for $\mathcal{L}_A$ is standard, the elements of its **domínio** can all be named by the standard numerals $\bar{0}, \bar{1}, \bar{2}, \dots$, O.s., the terms o, o', o'' , etc. Of course, this does not mean that the **membros** of $|\mathfrak{M}|$ are the numbers, just that we can pick them out the same way we can pick out the numbers in $|\mathfrak{N}|$. explanation

Problema 2.1. Show that the converse of [Proposição 2.2](#) is false, O.s., give an example of a [estrutura](#) $\mathfrak{M}$ with $|\mathfrak{M}| = \{\text{Val}^{\mathfrak{M}}(\bar{n}) : n \in \mathbb{N}\}$ that is not isomorphic to $\mathfrak{N}$.

Proposição 2.3. *If $\mathfrak{M} \models \mathbf{Q}$, and $|\mathfrak{M}| = \{\text{Val}^{\mathfrak{M}}(\bar{n}) : n \in \mathbb{N}\}$, then $\mathfrak{M}$ is [mod:mar:stm:prop:thq-standard](#) standard.*

Prova. We have to show that $\mathfrak{M}$ is isomorphic to $\mathfrak{N}$. Consider the function $g: \mathbb{N} \rightarrow |\mathfrak{M}|$ defined by $g(n) = \text{Val}^{\mathfrak{M}}(\bar{n})$. By the hypothesis, g is [sobrejetiva](#). It is also [injetiva](#): $\mathbf{Q} \vdash \bar{n} \neq \bar{m}$ whenever $n \neq m$. Thus, since $\mathfrak{M} \models \mathbf{Q}$, $\mathfrak{M} \models \bar{n} \neq \bar{m}$, whenever $n \neq m$. Thus, if $n \neq m$, then $\text{Val}^{\mathfrak{M}}(\bar{n}) \neq \text{Val}^{\mathfrak{M}}(\bar{m})$, O.s., $g(n) \neq g(m)$.

We also have to verify that g is an isomorphism.

1. We have $g(o^{\mathfrak{N}}) = g(0)$ since, $o^{\mathfrak{N}} = 0$. By definition of g , $g(0) = \text{Val}^{\mathfrak{M}}(\bar{0})$. But $\bar{0}$ is just o , and the value of a term which happens to be a [símbolo de constante](#) is given by what the [estrutura](#) assigns to that [símbolo de constante](#), O.s., $\text{Val}^{\mathfrak{M}}(o) = o^{\mathfrak{M}}$. So we have $g(o^{\mathfrak{N}}) = o^{\mathfrak{M}}$ as required.
2. $g(\iota^{\mathfrak{N}}(n)) = g(n+1)$, since ι in $\mathfrak{N}$ is the successor function on $\mathbb{N}$. Then, $g(n+1) = \text{Val}^{\mathfrak{M}}(\overline{n+1})$ by definition of g . But $\overline{n+1}$ is the same term as $\bar{n}'$, so $\text{Val}^{\mathfrak{M}}(\overline{n+1}) = \text{Val}^{\mathfrak{M}}(\bar{n}')$. By the definition of the value function, this is $= \iota^{\mathfrak{M}}(\text{Val}^{\mathfrak{M}}(\bar{n}))$. Since $\text{Val}^{\mathfrak{M}}(\bar{n}) = g(n)$ we get $g(\iota^{\mathfrak{N}}(n)) = \iota^{\mathfrak{M}}(g(n))$.
3. $g(+^{\mathfrak{N}}(n, m)) = g(n+m)$, since $+$ in $\mathfrak{N}$ is the addition function on $\mathbb{N}$. Then, $g(n+m) = \text{Val}^{\mathfrak{M}}(\overline{n+m})$ by definition of g . But $\mathbf{Q} \vdash \overline{n+m} = (\bar{n} + \bar{m})$, so $\text{Val}^{\mathfrak{M}}(\overline{n+m}) = \text{Val}^{\mathfrak{M}}(\bar{n} + \bar{m})$. By the definition of the value function, this is $= +^{\mathfrak{M}}(\text{Val}^{\mathfrak{M}}(\bar{n}), \text{Val}^{\mathfrak{M}}(\bar{m}))$. Since $\text{Val}^{\mathfrak{M}}(\bar{n}) = g(n)$ and $\text{Val}^{\mathfrak{M}}(\bar{m}) = g(m)$, we get $g(+^{\mathfrak{N}}(n, m)) = +^{\mathfrak{M}}(g(n), g(m))$.
4. $g(\times^{\mathfrak{N}}(n, m)) = \times^{\mathfrak{M}}(g(n), g(m))$: Exercise.
5. $\langle n, m \rangle \in <^{\mathfrak{N}}$ iff $n < m$. If $n < m$, then $\mathbf{Q} \vdash \bar{n} < \bar{m}$, and also $\mathfrak{M} \models \bar{n} < \bar{m}$. Thus $\langle \text{Val}^{\mathfrak{M}}(\bar{n}), \text{Val}^{\mathfrak{M}}(\bar{m}) \rangle \in <^{\mathfrak{M}}$, O.s., $\langle g(n), g(m) \rangle \in <^{\mathfrak{M}}$. If $n \not< m$, then $\mathbf{Q} \vdash \neg \bar{n} < \bar{m}$, and consequently $\mathfrak{M} \not\models \bar{n} < \bar{m}$. Thus, as before, $\langle g(n), g(m) \rangle \notin <^{\mathfrak{M}}$. Together, we get: $\langle n, m \rangle \in <^{\mathfrak{N}}$ iff $\langle g(n), g(m) \rangle \in <^{\mathfrak{M}}$. $\square$

[explanation](#)

The function g is the most obvious way of defining a mapping from $\mathbb{N}$ to the domain of any other [estrutura](#) $\mathfrak{M}$ for $\mathcal{L}_A$, since every such $\mathfrak{M}$ contains [membros](#) named by $\bar{0}, \bar{1}, \bar{2}$, etc. So it isn't surprising that if $\mathfrak{M}$ makes at least some basic statements about the $\bar{n}$'s true in the same way that $\mathfrak{N}$ does, and g is also bijective, then g will turn into an isomorphism. In fact, if $|\mathfrak{M}|$ contains no [membros](#) other than what the $\bar{n}$'s name, it's the only one.

Proposição 2.4. *If $\mathfrak{M}$ is standard, then g from the proof of [Proposição 2.3](#) is the only isomorphism from $\mathfrak{N}$ to $\mathfrak{M}$.* [mod:mar:stm:prop:thq-unique-iso](#)

Prova. Suppose $h: \mathbb{N} \rightarrow |\mathfrak{M}|$ is an isomorphism between $\mathfrak{N}$ and $\mathfrak{M}$. We show that $g = h$ by induction on n . If $n = 0$, then $g(0) = o^{\mathfrak{M}}$ by definition of g . But since h is an isomorphism, $h(0) = h(o^{\mathfrak{N}}) = o^{\mathfrak{M}}$, so $g(0) = h(0)$.

Now consider the case for $n + 1$. We have

$$\begin{aligned}
g(n+1) &= \text{Val}^{\mathfrak{M}}(\overline{n+1}) \text{ by definition of } g \\
&= \text{Val}^{\mathfrak{M}}(\overline{n'}) \text{ since } \overline{n+1} \equiv \overline{n'} \\
&= \iota^{\mathfrak{M}}(\text{Val}^{\mathfrak{M}}(\overline{n})) \text{ by definition of } \text{Val}^{\mathfrak{M}}(t') \\
&= \iota^{\mathfrak{M}}(g(n)) \text{ by definition of } g \\
&= \iota^{\mathfrak{M}}(h(n)) \text{ by induction hypothesis} \\
&= h(\iota^{\mathfrak{N}}(n)) \text{ since } h \text{ is an isomorphism} \\
&= h(n+1)
\end{aligned}$$

□

For any **infinito enumerável** set M , there's **uma bijeção** between $\mathbb{N}$ and M , explanation so every such set M is potentially the **domínio** of a standard model $\mathfrak{M}$. In fact, once you pick an object $z \in M$ and a suitable function s as $o^{\mathfrak{M}}$ and $\iota^{\mathfrak{M}}$, the interpretations of $+$, $\times$, and $<$ is already fixed. Only functions $s: M \rightarrow M \setminus \{z\}$ that are both **injetiva** and **sobrejetiva** are suitable in a standard model as $\iota^{\mathfrak{M}}$. The range of s cannot contain z , since otherwise $\forall x \, o \neq x'$ would be false. That **sentença** is true in $\mathfrak{N}$, and so $\mathfrak{M}$ also has to make it true. The function s has to be **injetiva**, since the successor function $\iota^{\mathfrak{N}}$ in $\mathfrak{N}$ is, and that $\iota^{\mathfrak{N}}$ is **injetiva** is expressed by a **sentença** true in $\mathfrak{N}$. It has to be **sobrejetiva** because otherwise there would be some $x \in M \setminus \{z\}$ not in the domain of s , O.s., the **sentença** $\forall x (x = o \vee \exists y \, y' = x)$ would be false in $\mathfrak{M}$ —but it is true in $\mathfrak{N}$.

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2.3 Non-Standard Models

We call a **estrutura** for $\mathcal{L}_A$ standard if it is isomorphic to $\mathfrak{N}$. If a **estrutura** explanation isn't isomorphic to $\mathfrak{N}$, it is called non-standard.

Definição 2.5. A **estrutura** $\mathfrak{M}$ for $\mathcal{L}_A$ is *non-standard* if it is not isomorphic to $\mathfrak{N}$. The **membros** $x \in |\mathfrak{M}|$ which are equal to $\text{Val}^{\mathfrak{M}}(\overline{n})$ for some $n \in \mathbb{N}$ are called *standard numbers* (of $\mathfrak{M}$), and those not, *non-standard numbers*.

By **Proposição 2.2**, any standard **estrutura** for $\mathcal{L}_A$ contains only standard **membros**. explanation Consequently, a non-standard **estrutura** must contain at least one non-standard element. In fact, the existence of a non-standard **membro** guarantees that the **estrutura** is non-standard.

Proposição 2.6. If a **estrutura** $\mathfrak{M}$ for $\mathcal{L}_A$ contains a non-standard number, $\mathfrak{M}$ is non-standard.

Prova. Suppose not, O.s., suppose $\mathfrak{M}$ standard but contains a non-standard number x . Let $g: \mathbb{N} \rightarrow |\mathfrak{M}|$ be an isomorphism. It is easy to see (by induction

on n) that $g(\text{Val}^{\mathfrak{M}}(\bar{n})) = \text{Val}^{\mathfrak{M}}(\bar{n})$. In other words, g maps standard numbers of $\mathfrak{N}$ to standard numbers of $\mathfrak{M}$. If $\mathfrak{M}$ contains a non-standard number, g cannot be *sobrejetiva*, contrary to hypothesis. $\square$

Problema 2.2. Recall that $\mathbf{Q}$ contains the axioms

$$\forall x \forall y (x' = y' \rightarrow x = y) \quad (Q_1)$$

$$\forall x \ 0 \neq x' \quad (Q_2)$$

$$\forall x (x = 0 \vee \exists y x = y') \quad (Q_3)$$

Give *estruturas* $\mathfrak{M}_1, \mathfrak{M}_2, \mathfrak{M}_3$ such that

1. $\mathfrak{M}_1 \models Q_1, \mathfrak{M}_1 \models Q_2, \mathfrak{M}_1 \not\models Q_3$;
2. $\mathfrak{M}_2 \models Q_1, \mathfrak{M}_2 \not\models Q_2, \mathfrak{M}_2 \models Q_3$; and
3. $\mathfrak{M}_3 \not\models Q_1, \mathfrak{M}_3 \models Q_2, \mathfrak{M}_3 \models Q_3$;

Obviously, you just have to specify $0^{\mathfrak{M}_i}$ and $i^{\mathfrak{M}_i}$ for each.

explanation

It is easy enough to specify non-standard *estruturas* for $\mathcal{L}_A$. For instance, take the structure with *domínio* $\mathbb{Z}$ and interpret all non-logical symbols as usual. Since negative numbers are not values of $\bar{n}$ for any n , this structure is non-standard. Of course, it will not be a *model* of arithmetic in the sense that it makes the same sentences true as $\mathfrak{N}$. For instance, $\forall x x' \neq 0$ is false. However, we can prove that non-standard models of arithmetic exist easily enough, using the compactness theorem.

Proposição 2.7. *Let $\mathbf{TA} = \{\varphi : \mathfrak{N} \models \varphi\}$ be the theory of $\mathfrak{N}$. $\mathbf{TA}$ has a *enumerável* non-standard model.*

Prova. Expand $\mathcal{L}_A$ by a new *símbolo de constante* c and consider the set of *sentenças*

$$\Gamma = \mathbf{TA} \cup \{c \neq \bar{0}, c \neq \bar{1}, c \neq \bar{2}, \dots\}$$

Any model $\mathfrak{M}^c$ of Γ would contain *um membro* $x = c^{\mathfrak{M}}$ which is non-standard, since $x \neq \text{Val}^{\mathfrak{M}}(\bar{n})$ for all $n \in \mathbb{N}$. Also, obviously, $\mathfrak{M}^c \models \mathbf{TA}$, since $\mathbf{TA} \subseteq \Gamma$. If we turn $\mathfrak{M}^c$ into a *estrutura* $\mathfrak{M}$ for $\mathcal{L}_A$ simply by forgetting about c , its domain still contains the non-standard x , and also $\mathfrak{M} \models \mathbf{TA}$. The latter is guaranteed since c does not occur in $\mathbf{TA}$. So, it suffices to show that Γ has a model.

We use the compactness theorem to show that Γ has a model. If every finite subset of Γ is satisfiable, so is Γ . Consider any finite subset $\Gamma_0 \subseteq \Gamma$. Γ_0 includes some *sentenças* of $\mathbf{TA}$ and some of the form $c \neq \bar{n}$, but only finitely many. Suppose k is the largest number so that $c \neq \bar{k} \in \Gamma_0$. Define $\mathfrak{N}_k$ by expanding $\mathfrak{N}$ to include the interpretation $c^{\mathfrak{N}_k} = k + 1$. $\mathfrak{N}_k \models \Gamma_0$: if $\varphi \in \mathbf{TA}$, $\mathfrak{N}_k \models \varphi$ since $\mathfrak{N}_k$ is just like $\mathfrak{N}$ in all respects except c , and c does not occur in φ . And $\mathfrak{N}_k \models c \neq \bar{n}$, since $n \leq k$, and $\text{Val}^{\mathfrak{N}_k}(c) = k + 1$. Thus, every finite subset of Γ is satisfiable. $\square$

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2.4 Models of $\mathbf{Q}$

We know that there are non-standard **estruturas** that make the same **sentenças** explanation true as $\mathfrak{N}$ does, O.s., is a model of **TA**. Since $\mathfrak{N} \models \mathbf{Q}$, any model of **TA** is also a model of **Q**. **Q** is much weaker than **TA**, p.ex., $\mathbf{Q} \not\models \forall x \forall y (x + y) = (y + x)$. Weaker theories are easier to satisfy: they have more models. P.ex., **Q** has models which make $\forall x \forall y (x + y) = (y + x)$ false, but those cannot also be models of **TA**, or **PA** for that matter. Models of **Q** are also relatively simple: we can specify them explicitly.

mod:mar:mdq;
ex:model-K-of-Q **Exemplo 2.8.** Consider the **estrutura** $\mathfrak{K}$ with domain $|\mathfrak{K}| = \mathbb{N} \cup \{a\}$ and interpretations

$$\begin{aligned} 0^{\mathfrak{K}} &= 0 \\ \iota^{\mathfrak{K}}(x) &= \begin{cases} x + 1 & \text{if } x \in \mathbb{N} \\ a & \text{if } x = a \end{cases} \\ +^{\mathfrak{K}}(x, y) &= \begin{cases} x + y & \text{if } x, y \in \mathbb{N} \\ a & \text{otherwise} \end{cases} \\ \times^{\mathfrak{K}}(x, y) &= \begin{cases} xy & \text{if } x, y \in \mathbb{N} \\ 0 & \text{if } x = 0 \text{ or } y = 0 \\ a & \text{otherwise} \end{cases} \\ <^{\mathfrak{K}} &= \{\langle x, y \rangle : x, y \in \mathbb{N} \text{ and } x < y\} \cup \{\langle x, a \rangle : x \in |\mathfrak{K}|\} \end{aligned}$$

To show that $\mathfrak{K} \models \mathbf{Q}$ we have to verify that all axioms of **Q** are true in $\mathfrak{K}$. For convenience, let's write x^* for $\iota^{\mathfrak{K}}(x)$ (the “successor” of x in $\mathfrak{K}$), $x \oplus y$ for $+^{\mathfrak{K}}(x, y)$ (the “sum” of x and y in $\mathfrak{K}$), $x \otimes y$ for $\times^{\mathfrak{K}}(x, y)$ (the “product” of x and y in $\mathfrak{K}$), and $x \odot y$ for $\langle x, y \rangle \in <^{\mathfrak{K}}$. With these abbreviations, we can give the operations in $\mathfrak{K}$ more perspicuously as

x	x^*	$x \oplus y$	0	m	a	$x \otimes y$	0	m	a
n	$n + 1$	0	0	m	a	0	0	0	0
a	a	n	n	$n + m$	a	n	0	nm	a
		a	a	a	a	a	0	a	a

We have $n \odot m$ iff $n < m$ for $n, m \in \mathbb{N}$ and $x \odot a$ for all $x \in |\mathfrak{K}|$.

$\mathfrak{K} \models \forall x \forall y (x' = y' \rightarrow x = y)$ since $*$ is **injetiva**. $\mathfrak{K} \models \forall x 0 \neq x'$ since 0 is not a $*$ -successor in $\mathfrak{K}$. $\mathfrak{K} \models \forall x (x = 0 \vee \exists y x = y')$ since for every $n > 0$, $n = (n - 1)^*$, and $a = a^*$.

$\mathfrak{K} \models \forall x (x + 0) = x$ since $n \oplus 0 = n + 0 = n$, and $a \oplus 0 = a$ by definition of $\oplus$. $\mathfrak{K} \models \forall x \forall y (x + y') = (x + y)'$ is a bit trickier. If n, m are both standard, we have:

$$(n \oplus m^*) = (n + (m + 1)) = (n + m) + 1 = (n \oplus m)^*$$

since $\oplus$ and $*$ agree with $+$ and $\cdot$ on standard numbers. Now suppose $x \in |\mathfrak{K}|$. Then

$$(x \oplus a^*) = (x \oplus a) = a = a^* = (x \oplus a)^*$$

The remaining case is if $y \in |\mathfrak{K}|$ but $x = a$. Here we also have to distinguish cases according to whether $y = n$ is standard or $y = b$:

$$\begin{aligned} (a \oplus n^*) &= (a \oplus (n+1)) = a = a^* = (a \oplus n)^* \\ (a \oplus a^*) &= (a \oplus a) = a = a^* = (a \oplus a)^* \end{aligned}$$

This is of course a bit more detailed than needed. For instance, since $a \oplus z = a$ whatever z is, we can immediately conclude $a \oplus a^* = a$. The remaining axioms can be verified the same way.

$\mathfrak{K}$ is thus a model of $\mathbf{Q}$. Its “addition” $\oplus$ is also commutative. But there are other sentences true in $\mathfrak{N}$ but false in $\mathfrak{K}$, and vice versa. For instance, $a \otimes a$, so $\mathfrak{K} \models \exists x x < x$ and $\mathfrak{K} \not\models \forall x \neg x < x$. This shows that $\mathbf{Q} \not\models \forall x \neg x < x$.

Problema 2.3. Prove that $\mathfrak{K}$ from [Exemplo 2.8](#) satisfies the remaining axioms of $\mathbf{Q}$,

$$\forall x (x \times 0) = 0 \tag{Q_6}$$

$$\forall x \forall y (x \times y') = ((x \times y) + x) \tag{Q_7}$$

$$\forall x \forall y (x < y \leftrightarrow \exists z (z' + x) = y) \tag{Q_8}$$

Find a [sentença](#) only involving $\cdot$ true in $\mathfrak{N}$ but false in $\mathfrak{K}$.

Exemplo 2.9. Consider the [estrutura](#) $\mathfrak{L}$ with domain $|\mathfrak{L}| = \mathbb{N} \cup \{a, b\}$ and interpretations $\cdot^{\mathfrak{L}} = *$, $+^{\mathfrak{L}} = \oplus$ given by [mod:mar:mdq:ex:model-L-of-Q](#)

x	x^*	$x \oplus y$	m	a	b
n	$n+1$	n	$n+m$	b	a
a	a	a	a	b	a
b	b	b	b	b	a

Since $*$ is [injetiva](#), 0 is not in its range, and every $x \in |\mathfrak{L}|$ other than 0 is, axioms Q_1 – Q_3 are true in $\mathfrak{L}$. For any x , $x \oplus 0 = x$, so Q_4 is true as well. For Q_5 , consider $x \oplus y^*$ and $(x \oplus y)^*$. They are equal if x and y are both standard, since then $*$ and $\oplus$ agree with $\cdot$ and $+$. If x is non-standard, and y is standard, we have $x \oplus y^* = x = x^* = (x \oplus y)^*$. If x and y are both non-standard, we have four cases:

$$\begin{aligned} a \oplus a^* &= b = b^* = (a \oplus a)^* \\ b \oplus b^* &= a = a^* = (b \oplus b)^* \\ b \oplus a^* &= b = b^* = (b \oplus y)^* \\ a \oplus b^* &= a = a^* = (a \oplus b)^* \end{aligned}$$

If x is standard, but y is non-standard, we have

$$\begin{aligned} n \oplus a^* &= n \oplus a = b = b^* = (n \oplus a)^* \\ n \oplus b^* &= n \oplus b = a = a^* = (n \oplus b)^* \end{aligned}$$

So, $\mathfrak{L} \models Q_5$. However, $a \oplus 0 \neq 0 \oplus a$, so $\mathfrak{L} \not\models \forall x \forall y (x + y) = (y + x)$.

Problema 2.4. Expand $\mathfrak{L}$ of [Exemplo 2.9](#) to include $\otimes$ and $\ominus$ that interpret $\times$ and $<$. Show that your structure satisfies the remaining axioms of $\mathbf{Q}$,

$$\forall x (x \times 0) = 0 \quad (Q_6)$$

$$\forall x \forall y (x \times y') = ((x \times y) + x) \quad (Q_7)$$

$$\forall x \forall y (x < y \leftrightarrow \exists z (z' + x) = y) \quad (Q_8)$$

Problema 2.5. In $\mathfrak{L}$ of [Exemplo 2.9](#), $a^* = a$ and $b^* = b$. Is there a model of $\mathbf{Q}$ in which $a^* = b$ and $b^* = a$?

We've explicitly constructed models of $\mathbf{Q}$ in which the non-standard [membros](#) live “beyond” the standard elements. In fact, that much is required by the axioms. A non-standard [membro](#) x cannot be $\ominus 0$, since $\mathbf{Q} \vdash \forall x \neg x < 0$ (see ??). Also, for every n , $\mathbf{Q} \vdash \forall x (x < \bar{n}' \rightarrow (x = \bar{0} \vee x = \bar{1} \vee \dots \vee x = \bar{n}))$ (??), so we can't have $a \ominus n$ for any $n > 0$.

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2.5 Models of PA

Any non-standard model of $\mathbf{TA}$ is also one of $\mathbf{PA}$. We know that non-standard models of $\mathbf{TA}$ and hence of $\mathbf{PA}$ exist. We also know that such non-standard models contain non-standard “numbers,” O.s., [membros](#) of the domain that are “beyond” all the standard “numbers.” But how are they arranged? How many are there? We've seen that models of the weaker theory $\mathbf{Q}$ can contain as few as a single non-standard number. But these simple [estruturas](#) are not models of $\mathbf{PA}$ or $\mathbf{TA}$.

The key to understanding the structure of models of $\mathbf{PA}$ or $\mathbf{TA}$ is to see what facts are [derivável](#) in these theories. For instance, already $\mathbf{PA}$ proves that $\forall x x \neq x'$ and $\forall x \forall y (x + y) = (y + x)$, so this rules out simple structures (in which these [sentenças](#) are false) as models of $\mathbf{PA}$.

Suppose $\mathfrak{M}$ is a model of $\mathbf{PA}$. Then if $\mathbf{PA} \vdash \varphi$, $\mathfrak{M} \models \varphi$. Let's again use $\mathbf{z}$ for $\mathbf{o}^{\mathfrak{M}}$, $*$ for $\mathbf{r}^{\mathfrak{M}}$, $\oplus$ for $\mathbf{+}^{\mathfrak{M}}$, $\otimes$ for $\mathbf{\times}^{\mathfrak{M}}$, and $\ominus$ for $\mathbf{<}^{\mathfrak{M}}$. Any [sentença](#) φ then states some condition about $\mathbf{z}$, $*$, $\oplus$, $\otimes$, and $\ominus$, and if $\mathfrak{M} \models \varphi$ that condition must be satisfied. For instance, if $\mathfrak{M} \models Q_1$, O.s., $\mathfrak{M} \models \forall x \forall y (x' = y' \rightarrow x = y)$, then $*$ must be [injetiva](#).

Proposição 2.10. In $\mathfrak{M}$, $\ominus$ is a linear strict order, O.s., it satisfies:

1. Not $x \ominus x$ for any $x \in |\mathfrak{M}|$.

2. If $x \otimes y$ and $y \otimes z$ then $x \otimes z$.
3. For any $x \neq y$, $x \otimes y$ or $y \otimes x$

Prova. **PA** proves:

1. $\forall x \neg x < x$
2. $\forall x \forall y \forall z ((x < y \wedge y < z) \rightarrow x < z)$
3. $\forall x \forall y ((x < y \vee y < x) \vee x = y)$ □

Proposição 2.11. $\mathbf{z}$ is the least *membro* of $|\mathfrak{M}|$ in the $\otimes$ -ordering. For any x , $x \otimes x^*$, and x^* is the $\otimes$ -least *membro* with that property. For any x , there is a unique y such that $y^* = x$. (We call y the “predecessor” of x in $\mathfrak{M}$, and denote it by *x .) mod:mar:mpa:
prop:M-discrete

Prova. Exercise. □

Problema 2.6. Find *sentenças* in $\mathcal{L}_A$ *derivável* in **PA** (and hence true in $\mathfrak{N}$) which guarantee the properties of $\mathbf{z}$, $*$, and $\otimes$ in **Proposição 2.11**

Proposição 2.12. All standard *membros* of $\mathfrak{M}$ are less than (according to $\otimes$) all non-standard *membros*.

Prova. We’ll use n as short for $\text{Val}^{\mathfrak{M}}(\bar{n})$, a standard *membro* of $\mathfrak{M}$. Already **Q** proves that, for any $n \in \mathbb{N}$, $\forall x (x < \bar{n}' \rightarrow (x = \bar{0} \vee x = \bar{1} \vee \dots \vee x = \bar{n}))$. There are no *membros* that are $\otimes \mathbf{z}$. So if n is standard and x is non-standard, we cannot have $x \otimes n$. By definition, a non-standard element is one that isn’t $\text{Val}^{\mathfrak{M}}(\bar{n})$ for any $n \in \mathbb{N}$, so $x \neq n$ as well. Since $\otimes$ is a linear order, we must have $n \otimes x$. □

Proposição 2.13. Every nonstandard *membro* x of $|\mathfrak{M}|$ is an element of the subset

$$\dots {}^{***}x \otimes {}^{**}x \otimes {}^*x \otimes x \otimes x \otimes x^* \otimes x^{**} \otimes x^{***} \otimes \dots$$

We call this subset the block of x and write it as $[x]$. It has no least and no greatest *membro*. It can be characterized as the set of those $y \in |\mathfrak{M}|$ such that, for some standard n , $x \oplus n = y$ or $y \oplus n = x$.

Prova. Clearly, such a set $[x]$ always exists since every *membro* y of $|\mathfrak{M}|$ has a unique successor y^* and unique predecessor *y . For successive *membros* y , y^* we have $y \otimes y^*$ and y^* is the $\otimes$ -least *membro* of $|\mathfrak{M}|$ such that y is $\otimes$ -less than it. Since always ${}^*y \otimes y$ and $y \otimes y^*$, $[x]$ has no least or greatest *membro*. If $y \in [x]$ then $x \in [y]$, for then either $y^{***} = x$ or $x^{***} = y$. If $y^{***} = x$ (with n $*$ ’s), then $y \oplus n = x$ and conversely, since **PA** $\vdash \forall x x' \dots' = (x + \bar{n})$ (if n is the number of r ’s). □

Proposição 2.14. *If $[x] \neq [y]$ and $x \otimes y$, then for any $u \in [x]$ and any $v \in [y]$, $u \otimes v$.*

Prova. Note that $\mathbf{PA} \vdash \forall x \forall y (x < y \rightarrow (x' < y \vee x' = y))$. Thus, if $u \otimes v$, we also have $u \oplus n^* \otimes v$ for any n if $[u] \neq [v]$.

Any $u \in [x]$ is $\otimes y$: $x \otimes y$ by assumption. If $u \otimes x$, $u \otimes y$ by transitivity. And if $x \otimes u$ but $u \in [x]$, we have $u = x \oplus n^*$ for some n , and so $u \otimes y$ by the fact just proved.

Now suppose that $v \in [y]$ is $\otimes y$, O.s., $v \oplus m^* = y$ for some standard m . This rules out $v \otimes x$, otherwise $y = v \oplus m^* \otimes x$. Clearly also, $x \neq v$, otherwise $x \oplus m^* = v \oplus m^* = y$ and we would have $[x] = [y]$. So, $x \otimes v$. But then also $x \oplus n^* \otimes v$ for any n . Hence, if $x \otimes u$ and $u \in [x]$, we have $u \otimes v$. If $u \otimes x$ then $u \otimes v$ by transitivity.

Lastly, if $y \otimes v$, $u \otimes v$ since, as we've shown, $u \otimes y$ and $y \otimes v$. $\square$

Corolário 2.15. *If $[x] \neq [y]$, $[x] \cap [y] = \emptyset$.*

Prova. Suppose $z \in [x]$ and $x \otimes y$. Then $z \otimes u$ for all $u \in [y]$. If $z \in [y]$, we would have $z \otimes z$. Similarly if $y \otimes x$. $\square$

This means that the blocks themselves can be ordered in a way that respects $\otimes$: $[x] \otimes [y]$ iff $x \otimes y$, or, equivalently, if $u \otimes v$ for any $u \in [x]$ and $v \in [y]$. Clearly, the standard block $[0]$ is the least block. It intersects with no non-standard block, and no two non-standard blocks intersect either. Specifically, you cannot “reach” a different block by taking repeated successors or predecessors. explanation

Proposição 2.16. *If x and y are non-standard, then $x \otimes x \oplus y$ and $x \oplus y \notin [x]$.*

Prova. If y is nonstandard, then $y \neq \mathbf{z}$. $\mathbf{PA} \vdash \forall x (y \neq 0 \rightarrow x < (x + y))$. Now suppose $x \oplus y \in [x]$. Since $x \otimes x \oplus y$, we would have $x \oplus n^* = x \oplus y$. But $\mathbf{PA} \vdash \forall x \forall y \forall z ((x + y) = (x + z) \rightarrow y = z)$ (the cancellation law for addition). This would mean $y = n^*$ for some standard n ; but y is assumed to be non-standard. $\square$

Proposição 2.17. *There is no least non-standard block.*

Prova. $\mathbf{PA} \vdash \forall x \exists y ((y + y) = x \vee (y + y)' = x)$, O.s., that every x is divisible by 2 (possibly with remainder 1). If x is non-standard, so is y . By the preceding proposition, $y \otimes y \oplus y$ and $y \oplus y \notin [y]$. Then also $y \otimes (y \oplus y)^*$ and $(y \oplus y)^* \notin [y]$. But $x = y \oplus y$ or $x = (y \oplus y)^*$, so $y \otimes x$ and $y \notin [x]$. $\square$

Proposição 2.18. *There is no largest block.*

Prova. Exercise. $\square$

Problema 2.7. Show that in a non-standard model of $\mathbf{PA}$, there is no largest block.

Proposição 2.19. *The ordering of the blocks is dense. That is, if $x \otimes y$ and $[x] \neq [y]$, then there is a block $[z]$ distinct from both that is between them.* *mod:mar:mpa: prop:blocks-dense*

Prova. Suppose $x \otimes y$. As before, $x \oplus y$ is divisible by two (possibly with remainder): there is a $z \in |\mathfrak{M}|$ such that either $x \oplus y = z \oplus z$ or $x \oplus y = (z \oplus z)^*$. The element z is the “average” of x and y , and $x \otimes z$ and $z \otimes y$. $\square$

Problema 2.8. Write out a detailed proof of **Proposição 2.19**. Which **sentença** must **PA** **deriva** in order to guarantee the existence of z ? Why is $x \otimes z$ and $z \otimes y$, and why is $[x] \neq [z]$ and $[z] \neq [y]$?

explanation The non-standard blocks are therefore ordered like the rationals: they form a **infinito enumerável** dense linear ordering without endpoints. One can show that any two such **infinito enumerável** orderings are isomorphic. It follows that for any two **enumerável** non-standard models $\mathfrak{M}_1$ and $\mathfrak{M}_2$ of true arithmetic, their reducts to the language containing $<$ and $=$ only are isomorphic. Indeed, an isomorphism h can be defined as follows: the standard parts of $\mathfrak{M}_1$ and $\mathfrak{M}_2$ are isomorphic to the standard model $\mathfrak{N}$ and hence to each other. The blocks making up the non-standard part are themselves ordered like the rationals and therefore isomorphic; an isomorphism of the blocks can be extended to an isomorphism *within* the blocks by matching up arbitrary elements in each, and then taking the image of the successor of x in $\mathfrak{M}_1$ to be the successor of the image of x in $\mathfrak{M}_2$. Note that it does *not* follow that $\mathfrak{M}_1$ and $\mathfrak{M}_2$ are isomorphic in the full language of arithmetic (indeed, isomorphism is always relative to a **linguagem**), as there are non-isomorphic ways to define addition and multiplication over $|\mathfrak{M}_1|$ and $|\mathfrak{M}_2|$. (This also follows from a famous theorem due to Vaught that the number of countable models of a complete theory cannot be 2.)

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2.6 Computable Models of Arithmetic

explanation The standard model $\mathfrak{N}$ has two nice features. Its domain is the natural numbers $\mathbb{N}$, O.s., its elements are just the kinds of things we want to talk about using the language of arithmetic, and the standard numeral $\bar{n}$ actually picks out n . The other nice feature is that the interpretations of the non-logical symbols of $\mathcal{L}_A$ are all *computable*. The successor, addition, and multiplication functions which serve as $s^{\mathfrak{N}}$, $+$ $^{\mathfrak{N}}$, and $\times^{\mathfrak{N}}$ are computable functions of numbers. (Computable by Turing machines, or definable by primitive recursion, say.) And the less-than relation on $\mathfrak{N}$, O.s., $<^{\mathfrak{N}}$, is decidable.

Non-standard models of arithmetical theories such as **Q** and **PA** must contain non-standard elements. Thus their domains typically include **membros** in addition to $\mathbb{N}$. However, any countable **estrutura** can be built on any **infinito enumerável** set, including $\mathbb{N}$. So there are also non-standard models with domain $\mathbb{N}$. In such models $\mathfrak{M}$, of course, at least some numbers cannot play

the roles they usually play, since some k must be different from $\text{Val}^{\mathfrak{M}}(\bar{n})$ for all $n \in \mathbb{N}$.

Definição 2.20. A estrutura $\mathfrak{M}$ for $\mathcal{L}_A$ is *computable* iff $|\mathfrak{M}| = \mathbb{N}$ and $\iota^{\mathfrak{M}}$, $+\mathfrak{M}$, $\times^{\mathfrak{M}}$ are computable functions and $<^{\mathfrak{M}}$ is a decidable relation.

Exemplo 2.21. Recall the structure $\mathfrak{K}$ from Exemplo 2.8. Its domain was $|\mathfrak{K}| = \mathbb{N} \cup \{a\}$ and interpretations

$$\begin{aligned} o^{\mathfrak{K}} &= 0 \\ \iota^{\mathfrak{K}}(x) &= \begin{cases} x+1 & \text{if } x \in \mathbb{N} \\ a & \text{if } x = a \end{cases} \\ +^{\mathfrak{K}}(x, y) &= \begin{cases} x+y & \text{if } x, y \in \mathbb{N} \\ a & \text{otherwise} \end{cases} \\ \times^{\mathfrak{K}}(x, y) &= \begin{cases} xy & \text{if } x, y \in \mathbb{N} \\ 0 & \text{if } x = 0 \text{ or } y = 0 \\ a & \text{otherwise} \end{cases} \\ <^{\mathfrak{K}} &= \{\langle x, y \rangle : x, y \in \mathbb{N} \text{ and } x < y\} \cup \{\langle x, a \rangle : n \in |\mathfrak{K}|\} \end{aligned}$$

But $|\mathfrak{K}|$ is *infinito enumerável* and so is equinumerous with $\mathbb{N}$. For instance, $g: \mathbb{N} \rightarrow |\mathfrak{K}|$ with $g(0) = a$ and $g(n) = n+1$ for $n > 0$ is *uma bijeção*. We can turn it into an isomorphism between a new model $\mathfrak{K}'$ of $\mathbf{Q}$ and $\mathfrak{K}$. In $\mathfrak{K}'$, we have to assign different functions and relations to the symbols of $\mathcal{L}_A$, since different *membros* of $\mathbb{N}$ play the roles of standard and non-standard numbers.

Specifically, 0 now plays the role of a , not of the smallest standard number. The smallest standard number is now 1. So we assign $o^{\mathfrak{K}'} = 1$. The successor function is also different now: given a standard number, O.s., an $n > 0$, it still returns $n+1$. But 0 now plays the role of a , which is its own successor. So $\iota^{\mathfrak{K}'}(0) = 0$. For addition and multiplication we likewise have

$$\begin{aligned} +^{\mathfrak{K}'}(x, y) &= \begin{cases} x+y-1 & \text{if } x, y > 0 \\ 0 & \text{otherwise} \end{cases} \\ \times^{\mathfrak{K}'}(x, y) &= \begin{cases} 1 & \text{if } x = 1 \text{ or } y = 1 \\ xy-x-y+2 & \text{if } x, y > 1 \\ 0 & \text{otherwise} \end{cases} \end{aligned}$$

And we have $\langle x, y \rangle \in <^{\mathfrak{K}'}$ iff $x < y$ and $x > 0$ and $y > 0$, or if $y = 0$.

All of these functions are computable functions of natural numbers and $<^{\mathfrak{K}'}$ is a decidable relation on $\mathbb{N}$ —but they are not the same functions as successor, addition, and multiplication on $\mathbb{N}$, and $<^{\mathfrak{K}'}$ is not the same relation as $<$ on $\mathbb{N}$.

Problema 2.9. Give a estrutura $\mathfrak{L}'$ with $|\mathfrak{L}'| = \mathbb{N}$ isomorphic to $\mathfrak{L}$ of Exemplo 2.9.

explanation Exemplo 2.21 shows that $\mathbf{Q}$ has computable non-standard models with domain $\mathbb{N}$. However, the following result shows that this is not true for models of $\mathbf{PA}$ (and thus also for models of $\mathbf{TA}$).

Teorema 2.22 (Tennenbaum's Theorem). *$\mathfrak{N}$ is the only computable model of $\mathbf{PA}$.*

Capítulo 3

The Interpolation Theorem

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3.1 Introduction

mod:int:int:
sec

The interpolation theorem is the following result: Suppose $\models \varphi \rightarrow \psi$. Then there is a **sentença** χ such that $\models \varphi \rightarrow \chi$ and $\models \chi \rightarrow \psi$. Moreover, every **símbolo de constante**, **símbolo de função**, and **símbolo de predicado** (other than $=$) in χ occurs both in φ and ψ . The **sentença** χ is called an *interpolant* of φ and ψ .

The interpolation theorem is interesting in its own right, but its main importance lies in the fact that it can be used to prove results about definability in a theory, and the conditions under which combining two consistent theories results in a consistent theory. The first result is known as the Beth definability theorem; the second, Robinson's joint consistency theorem.

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3.2 Separation of **Sentenças**

mod:int:sep:
sec

A bit of groundwork is needed before we can proceed with the proof of the interpolation theorem. An interpolant for φ and ψ is a **sentença** χ such that $\varphi \models \chi$ and $\chi \models \psi$. By contraposition, the latter is true iff $\neg\psi \models \neg\chi$. A **sentença** χ with this property is said to *separate* φ and $\neg\psi$. So finding an interpolant for φ and ψ amounts to finding a **sentença** that separates φ and $\neg\psi$. As so often, it will be useful to consider a generalization: a sentence that separates two *sets* of **sentenças**.

Definição 3.1. A sentence χ *separates* sets of sentences Γ and Δ if and only if $\Gamma \models \chi$ and $\Delta \models \neg\chi$. If no such **sentença** exists, then Γ and Δ are *inseparable*.

The inclusion relations between the classes of models of Γ , Δ and χ are represented below:

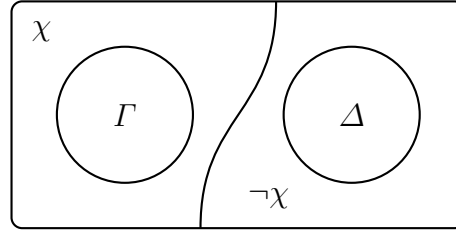


Figura 3.1: χ separates Γ and Δ

Lema 3.2. Suppose $\mathcal{L}_0$ is the language containing every *símbolo de constante*, *símbolo de função* and *símbolo de predicado* (other than $\doteq$) that occurs in both Γ and Δ , and let $\mathcal{L}'_0$ be obtained by the addition of infinitely many new *símbolos de constante* c_n for $n \geq 0$. Then if Γ and Δ are inseparable in $\mathcal{L}_0$, they are also inseparable in $\mathcal{L}'_0$.

mod:int:sep:
fig:sep
mod:int:sep:
lem:sep1

Prova. We proceed indirectly: suppose by way of contradiction that Γ and Δ are separated in $\mathcal{L}'_0$. Then $\Gamma \models \chi[c/x]$ and $\Delta \models \neg\chi[c/x]$ for some $\chi \in \mathcal{L}_0$ (where c is a new *símbolo de constante*—the case where χ contains more than one such new *símbolo de constante* is similar). By compactness, there are *finite* subsets Γ_0 of Γ and Δ_0 of Δ such that $\Gamma_0 \models \chi[c/x]$ and $\Delta_0 \models \neg\chi[c/x]$. Let γ be the conjunction of all *fórmulas* in Γ_0 and δ the conjunction of all *fórmulas* in Δ_0 . Then

$$\gamma \models \chi[c/x], \quad \delta \models \neg\chi[c/x].$$

From the former, by Generalization, we have $\gamma \models \forall x \chi$, and from the latter by contraposition, $\chi[c/x] \models \neg\delta$, whence also $\forall x \chi \models \neg\delta$. Contraposition again gives $\delta \models \neg\forall x \chi$. By monotonicity,

$$\Gamma \models \forall x \chi, \quad \Delta \models \neg\forall x \chi,$$

so that $\forall x \chi$ separates Γ and Δ in $\mathcal{L}_0$. □

Lema 3.3. Suppose that $\Gamma \cup \{\exists x \sigma\}$ and Δ are inseparable, and c is a new *símbolo de constante* not in Γ , Δ , or σ . Then $\Gamma \cup \{\exists x \sigma, \sigma[c/x]\}$ and Δ are also inseparable.

mod:int:sep:
lem:sep2

Prova. Suppose for contradiction that χ separates $\Gamma \cup \{\exists x \sigma, \sigma[c/x]\}$ and Δ , while at the same time $\Gamma \cup \{\exists x \sigma\}$ and Δ are inseparable. We distinguish two cases:

1. c does not occur in χ : in this case $\Gamma \cup \{\exists x \sigma, \neg\chi\}$ is satisfiable (otherwise χ separates $\Gamma \cup \{\exists x \sigma\}$ and Δ). It remains so if $\sigma[c/x]$ is added, so χ does not separate $\Gamma \cup \{\exists x \sigma, \sigma[c/x]\}$ and Δ after all.

2. c does occur in χ so that χ has the form $\chi[c/x]$. Then we have that

$$\Gamma \cup \{\exists x \sigma, \sigma[c/x]\} \models \chi[c/x],$$

whence $\Gamma, \exists x \sigma \models \forall x (\sigma \rightarrow \chi)$ by the Deduction Theorem and Generalization, and finally $\Gamma \cup \{\exists x \sigma\} \models \exists x \chi$. On the other hand, $\Delta \models \neg \chi[c/x]$ and hence by Generalization $\Delta \models \neg \exists x \chi$. So $\Gamma \cup \{\exists x \sigma\}$ and Δ are separable, a contradiction. $\square$

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3.3 Craig's Interpolation Theorem

mod:int:prf:
mod:int:prf:
thm:interpol

Teorema 3.4 (Craig's Interpolation Theorem). *If $\models \varphi \rightarrow \psi$, then there is a *sentença* χ such that $\models \varphi \rightarrow \chi$ and $\models \chi \rightarrow \psi$, and every *símbolo de constante*, *símbolo de função*, and *símbolo de predicado* (other than $=$) in χ occurs both in φ and ψ . The *sentença* χ is called an interpolant of φ and ψ .*

Prova. Suppose $\mathcal{L}_1$ is the language of φ and $\mathcal{L}_2$ is the language of ψ . Let $\mathcal{L}_0 = \mathcal{L}_1 \cap \mathcal{L}_2$. For each $i \in \{0, 1, 2\}$, let $\mathcal{L}'_i$ be obtained from $\mathcal{L}_i$ by adding the infinitely many new *símbolos de constante* $c_0, c_1, c_2, \dots$.

If φ is unsatisfiable, $\exists x x \neq x$ is an interpolant. If $\neg \psi$ is unsatisfiable (and hence ψ is valid), $\exists x x = x$ is an interpolant. So we may assume also that both φ and $\neg \psi$ are satisfiable.

In order to prove the contrapositive of the Interpolation Theorem, assume that there is no interpolant for φ and ψ . In other words, assume that $\{\varphi\}$ and $\{\neg \psi\}$ are inseparable in $\mathcal{L}_0$.

Our goal is to extend the pair $(\{\varphi\}, \{\neg \psi\})$ to a maximally inseparable pair (Γ^*, Δ^*) . Let $\varphi_0, \varphi_1, \varphi_2, \dots$ enumerate the *sentenças* of $\mathcal{L}_1$, and $\psi_0, \psi_1, \psi_2, \dots$ enumerate the *sentenças* of $\mathcal{L}_2$. We define two increasing sequences of sets of *sentenças* (Γ_n, Δ_n) , for $n \geq 0$, as follows. Put $\Gamma_0 = \{\varphi\}$ and $\Delta_0 = \{\neg \psi\}$. Assuming (Γ_n, Δ_n) are already defined, define Γ_{n+1} and Δ_{n+1} by:

1. If $\Gamma_n \cup \{\varphi_n\}$ and Δ_n are inseparable in $\mathcal{L}'_0$, put φ_n in Γ_{n+1} . Moreover, if φ_n is an existential *fórmula* $\exists x \sigma$ then pick a new *símbolo de constante* c not occurring in $\Gamma_n, \Delta_n, \varphi_n$ or ψ_n , and put $\sigma[c/x]$ in Γ_{n+1} .
2. If Γ_{n+1} and $\Delta_n \cup \{\psi_n\}$ are inseparable in $\mathcal{L}'_0$, put ψ_n in Δ_{n+1} . Moreover, if ψ_n is an existential *fórmula* $\exists x \sigma$, then pick a new *símbolo de constante* c not occurring in $\Gamma_{n+1}, \Delta_n, \varphi_n$ or ψ_n , and put $\sigma[c/x]$ in Δ_{n+1} .

Finally, define:

$$\Gamma^* = \bigcup_{n \geq 0} \Gamma_n, \quad \Delta^* = \bigcup_{n \geq 0} \Delta_n.$$

By simultaneous induction on n we can now prove:

1. Γ_n and Δ_n are inseparable in $\mathcal{L}'_0$;
2. Γ_{n+1} and Δ_n are inseparable in $\mathcal{L}'_0$.

mod:int:prf:
part-a
mod:int:prf:
part-b

The basis for (1) is given by [Lema 3.2](#). For part (2), we need to distinguish three cases:

1. If $\Gamma_0 \cup \{\varphi_0\}$ and Δ_0 are separable, then $\Gamma_1 = \Gamma_0$ and (2) is just (1);
2. If $\Gamma_1 = \Gamma_0 \cup \{\varphi_0\}$, then Γ_1 and Δ_0 are inseparable by construction.
3. It remains to consider the case where φ_0 is existential, so that $\Gamma_1 = \Gamma_0 \cup \{\exists x \sigma, \sigma[c/x]\}$. By construction, $\Gamma_0 \cup \{\exists x \sigma\}$ and Δ_0 are inseparable, so that by [Lema 3.3](#) also $\Gamma_0 \cup \{\exists x \sigma, \sigma[c/x]\}$ and Δ_0 are inseparable.

This completes the basis of the induction for (1) and (2) above. Now for the inductive step. For (1), if $\Delta_{n+1} = \Delta_n \cup \{\psi_n\}$ then Γ_{n+1} and Δ_{n+1} are inseparable by construction (even when ψ_n is existential, by [Lema 3.3](#)); if $\Delta_{n+1} = \Delta_n$ (because Γ_{n+1} and $\Delta_n \cup \{\psi_n\}$ are separable), then we use the induction hypothesis on (2). For the inductive step for (2), if $\Gamma_{n+2} = \Gamma_{n+1} \cup \{\varphi_{n+1}\}$ then Γ_{n+2} and Δ_{n+1} are inseparable by construction (even when φ_{n+1} is existential, by [Lema 3.3](#)); and if $\Gamma_{n+2} = \Gamma_{n+1}$ then we use the inductive case for (1) just proved. This concludes the induction on (1) and (2).

It follows that Γ^* and Δ^* are inseparable; if not, by compactness, there is $n \geq 0$ that separates Γ_n and Δ_n , against (1). In particular, Γ^* and Δ^* are consistent: for if the former or the latter is inconsistent, then they are separated by $\exists x x \neq x$ or $\forall x x = x$, respectively.

We now show that Γ^* is maximally consistent in $\mathcal{L}'_1$ and likewise Δ^* in $\mathcal{L}'_2$. For the former, suppose that $\varphi_n \notin \Gamma^*$ and $\neg\varphi_n \notin \Gamma^*$, for some $n \geq 0$. If $\varphi_n \notin \Gamma^*$ then $\Gamma_n \cup \{\varphi_n\}$ is separable from Δ_n , and so there is $\chi \in \mathcal{L}'_0$ such that both:

$$\Gamma^* \models \varphi_n \rightarrow \chi, \quad \Delta^* \models \neg\chi.$$

Likewise, if $\neg\varphi_n \notin \Gamma^*$, there is $\chi' \in \mathcal{L}'_0$ such that both:

$$\Gamma^* \models \neg\varphi_n \rightarrow \chi', \quad \Delta^* \models \neg\chi'.$$

By propositional logic, $\Gamma^* \models \chi \vee \chi'$ and $\Delta^* \models \neg(\chi \vee \chi')$, so $\chi \vee \chi'$ separates Γ^* and Δ^* . A similar argument establishes that Δ^* is maximal.

Finally, we show that $\Gamma^* \cap \Delta^*$ is maximally consistent in $\mathcal{L}'_0$. It is obviously consistent, since it is the intersection of consistent sets. To show maximality, let $\sigma \in \mathcal{L}'_0$. Now, Γ^* is maximal in $\mathcal{L}'_1 \supseteq \mathcal{L}'_0$, and similarly Δ^* is maximal in $\mathcal{L}'_2 \supseteq \mathcal{L}'_0$. It follows that either $\sigma \in \Gamma^*$ or $\neg\sigma \in \Gamma^*$, and either $\sigma \in \Delta^*$ or $\neg\sigma \in \Delta^*$. If $\sigma \in \Gamma^*$ and $\neg\sigma \in \Delta^*$ then σ would separate Γ^* and Δ^* ; and if $\neg\sigma \in \Gamma^*$ and $\sigma \in \Delta^*$ then Γ^* and Δ^* would be separated by $\neg\sigma$. Hence, either $\sigma \in \Gamma^* \cap \Delta^*$ or $\neg\sigma \in \Gamma^* \cap \Delta^*$, and $\Gamma^* \cap \Delta^*$ is maximal.

Since Γ^* is maximally consistent, it has a model $\mathfrak{M}'_1$ whose [domínio](#) $|\mathfrak{M}'_1|$ comprises all and only the elements $c^{\mathfrak{M}'_1}$ interpreting the [símbolos de constante](#)—just like in the proof of the completeness theorem (??). Similarly, Δ^*

has a model $\mathfrak{M}'_2$ whose **domínio** $|\mathfrak{M}'_2|$ is given by the interpretations $c^{\mathfrak{M}'_2}$ of the **símbolos de constante**.

Let $\mathfrak{M}_1$ be obtained from $\mathfrak{M}'_1$ by dropping interpretations for **símbolos de constante**, **símbolos de função**, and **símbolos de predicado** in $\mathcal{L}'_1 \setminus \mathcal{L}'_0$, and similarly for $\mathfrak{M}_2$. Then the map $h: M_1 \rightarrow M_2$ defined by $h(c^{\mathfrak{M}'_1}) = c^{\mathfrak{M}'_2}$ is an isomorphism in $\mathcal{L}'_0$, because $\Gamma^* \cap \Delta^*$ is maximally consistent in $\mathcal{L}'_0$, as shown. This follows because any $\mathcal{L}'_0$ -**sentença** either belongs to both Γ^* and Δ^* , or to neither: so $c^{\mathfrak{M}'_1} \in P^{\mathfrak{M}'_1}$ if and only if $P(c) \in \Gamma^*$ if and only if $P(c) \in \Delta^*$ if and only if $c^{\mathfrak{M}'_2} \in P^{\mathfrak{M}'_2}$. The other conditions satisfied by isomorphisms can be established similarly.

Let us now define a model $\mathfrak{M}$ for the **linguagem** $\mathcal{L}_1 \cup \mathcal{L}_2$ as follows:

1. The **domínio** $|\mathfrak{M}|$ is just $|\mathfrak{M}_2|$, O.s., the set of all elements $c^{\mathfrak{M}'_2}$;
2. If a **símbolo de predicado** P is in $\mathcal{L}_2 \setminus \mathcal{L}_1$ then $P^{\mathfrak{M}} = P^{\mathfrak{M}'_2}$;
3. If a predicate P is in $\mathcal{L}_1 \setminus \mathcal{L}_2$ then $P^{\mathfrak{M}} = h(P^{\mathfrak{M}'_2})$, O.s., $\langle c_1^{\mathfrak{M}'_2}, \dots, c_n^{\mathfrak{M}'_2} \rangle \in P^{\mathfrak{M}}$ if and only if $\langle c_1^{\mathfrak{M}'_1}, \dots, c_n^{\mathfrak{M}'_1} \rangle \in P^{\mathfrak{M}'_1}$.
4. If a **símbolo de predicado** P is in $\mathcal{L}_0$ then $P^{\mathfrak{M}} = P^{\mathfrak{M}'_2} = h(P^{\mathfrak{M}'_1})$.
5. **Símbolos de função** of $\mathcal{L}_1 \cup \mathcal{L}_2$, including **símbolos de constante**, are handled similarly.

Finally, one shows by induction on **fórmulas** that $\mathfrak{M}$ agrees with $\mathfrak{M}'_1$ on all **fórmulas** of $\mathcal{L}'_1$ and with $\mathfrak{M}'_2$ on all **fórmulas** of $\mathcal{L}'_2$. In particular, $\mathfrak{M} \models \Gamma^* \cup \Delta^*$, whence $\mathfrak{M} \models \varphi$ and $\mathfrak{M} \models \neg\psi$, and $\not\models \varphi \rightarrow \psi$. This concludes the proof of Craig's Interpolation Theorem. $\square$

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3.4 The Definability Theorem

mod:int:def:
sec One important application of the interpolation theorem is Beth's definability theorem. To define an n -place relation R we can give a **fórmula** χ with n free **variáveis** which does not involve R . This would be an *explicit* definition of R in terms of χ . We can then say also that a theory $\Sigma(P)$ in a **linguagem** containing the n -place **símbolo de predicado** P explicitly defines P if it contains (or at least entails) a formalized explicit definition, O.s.,

$$\Sigma(P) \models \forall x_1 \dots \forall x_n (P(x_1, \dots, x_n) \leftrightarrow \chi(x_1, \dots, x_n)).$$

But an explicit definition is only one way of defining—in the sense of determining completely—a relation. A theory may also be such that the interpretation of P is fixed by the interpretation of the rest of the **linguagem** in any model. The definability theorem states that whenever a theory fixes the interpretation of P in this way—whenever it *implicitly defines* P —then it also explicitly defines it.

Definição 3.5. Suppose $\mathcal{L}$ is a *linguagem* not containing the *símbolo de predicado* P . A set $\Sigma(P)$ of *sentenças* of $\mathcal{L} \cup \{P\}$ *explicitly defines* P if and only if there is a *fórmula* $\chi(x_1, \dots, x_n)$ of $\mathcal{L}$ such that

$$\Sigma(P) \models \forall x_1 \dots \forall x_n (P(x_1, \dots, x_n) \leftrightarrow \chi(x_1, \dots, x_n)).$$

Definição 3.6. Suppose $\mathcal{L}$ is a *linguagem* not containing the *símbolos de predicado* P and P' . A set $\Sigma(P)$ of *sentenças* of $\mathcal{L} \cup \{P\}$ *implicitly defines* P if and only if

$$\Sigma(P) \cup \Sigma(P') \models \forall x_1 \dots \forall x_n (P(x_1, \dots, x_n) \leftrightarrow P'(x_1, \dots, x_n)),$$

where $\Sigma(P')$ is the result of uniformly replacing P with P' in $\Sigma(P)$.

In other words, for any model $\mathfrak{M}$ and $R, R' \subseteq |\mathfrak{M}|^n$, if both $(\mathfrak{M}, R) \models \Sigma(P)$ and $(\mathfrak{M}, R') \models \Sigma(P')$, then $R = R'$; where $(\mathfrak{M}, R)$ is the *estrutura* $\mathfrak{M}'$ for the expansion of $\mathcal{L}$ to $\mathcal{L} \cup \{P\}$ such that $P^{\mathfrak{M}'} = R$, and similarly for $(\mathfrak{M}, R')$.

Teorema 3.7 (Beth Definability Theorem). *A set $\Sigma(P)$ of $\mathcal{L} \cup \{P\}$ -fórmulas implicitly defines P if and only $\Sigma(P)$ explicitly defines P .*

Prova. If $\Sigma(P)$ explicitly defines P then both

$$\begin{aligned} \Sigma(P) \models & \quad \forall x_1 \dots \forall x_n (P(x_1, \dots, x_n) \leftrightarrow \chi(x_1, \dots, x_n)) \\ \Sigma(P') \models & \quad \forall x_1 \dots \forall x_n (P'(x_1, \dots, x_n) \leftrightarrow \chi(x_1, \dots, x_n)) \end{aligned}$$

and the conclusion follows. For the converse: assume that $\Sigma(P)$ implicitly defines P . First, we add *símbolos de constante* $c_1, \dots, c_n$ to $\mathcal{L}$. Then

$$\Sigma(P) \cup \Sigma(P') \models P(c_1, \dots, c_n) \rightarrow P'(c_1, \dots, c_n).$$

By compactness, there are finite sets $\Delta_0 \subseteq \Sigma(P)$ and $\Delta_1 \subseteq \Sigma(P')$ such that

$$\Delta_0 \cup \Delta_1 \models P(c_1, \dots, c_n) \rightarrow P'(c_1, \dots, c_n).$$

Let $\theta(P)$ be the conjunction of all *sentenças* $\varphi(P)$ such that either $\varphi(P) \in \Delta_0$ or $\varphi(P') \in \Delta_1$ and let $\theta(P')$ be the conjunction of all *sentenças* $\varphi(P')$ such that either $\varphi(P) \in \Delta_0$ or $\varphi(P') \in \Delta_1$. Then $\theta(P) \wedge \theta(P') \models P(c_1, \dots, c_n) \rightarrow P'(c_1, \dots, c_n)$. We can re-arrange this so that each *símbolo de predicado* occurs on one side of $\models$:

$$\theta(P) \wedge P(c_1, \dots, c_n) \models \theta(P') \rightarrow P'(c_1, \dots, c_n).$$

By Craig's Interpolation Theorem there is a *sentença* $\chi(c_1, \dots, c_n)$ not containing P or P' such that:

$$\begin{aligned} \theta(P) \wedge P(c_1, \dots, c_n) \models & \quad \chi(c_1, \dots, c_n); \\ \chi(c_1, \dots, c_n) \models & \quad \theta(P') \rightarrow P'(c_1, \dots, c_n). \end{aligned}$$

From the former of these two entailments we have: $\theta(P) \models P(c_1, \dots, c_n) \rightarrow \chi(c_1, \dots, c_n)$. And from the latter, since an $\mathcal{L} \cup \{P\}$ -model $(\mathfrak{M}, R) \models \varphi(P)$ if and only if the corresponding $\mathcal{L} \cup \{P'\}$ -model $(\mathfrak{M}, R) \models \varphi(P')$, we have $\chi(c_1, \dots, c_n) \models \theta(P) \rightarrow P(c_1, \dots, c_n)$, from which:

$$\theta(P) \models \chi(c_1, \dots, c_n) \rightarrow P(c_1, \dots, c_n).$$

Putting the two together, $\theta(P) \models P(c_1, \dots, c_n) \leftrightarrow \chi(c_1, \dots, c_n)$, and by monotonicity and generalization also

$$\Sigma(P) \models \forall x_1 \dots \forall x_n (P(x_1, \dots, x_n) \leftrightarrow \chi(x_1, \dots, x_n)). \quad \square$$

Capítulo 4

Lindström's Theorem

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4.1 Introduction

In this chapter we aim to prove Lindström's characterization of first-order logic as the maximal logic for which (given certain further constraints) the Compactness and the Downward Löwenheim–Skolem theorems hold (?? and ??). First, we need a more general characterization of the general class of logics to which the theorem applies. We will restrict ourselves to *relational* languages, O.s., languages which only contain **símbolos de predicado** and individual constants, but no **símbolos de função**.

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4.2 Abstract Logics

Definição 4.1. An *abstract logic* is a pair $\langle L, \models_L \rangle$, where L is a function that assigns to each **linguagem** $\mathcal{L}$ a set $L(\mathcal{L})$ of **sentenças**, and $\models_L$ is a relation between **estruturas** for the **linguagem** $\mathcal{L}$ and **membros** of $L(\mathcal{L})$. In particular, $\langle F, \models \rangle$ is ordinary first-order logic, O.s., F is the function assigning to the **linguagem** $\mathcal{L}$ the set of first-order **sentenças** built from the constants in $\mathcal{L}$, and $\models$ is the satisfaction relation of first-order logic.

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Notice that we are still employing the same notion of **estrutura** for a given **linguagem** as for first-order logic, but we do not presuppose that **sentenças** are build up from the basic symbols in $\mathcal{L}$ in the usual way, nor that the relation $\models_L$ is recursively defined in the same way as for first-order logic. So for instance the definition, being completely general, is intended to capture the case where **sentenças** in $\langle L, \models_L \rangle$ contain infinitely long conjunctions or disjunction, or quantifiers other than $\exists$ and $\forall$ (p.ex., “there are infinitely many x such that ...”), or perhaps infinitely long quantifier prefixes. To emphasize that

“*sentenças*” in $L(\mathcal{L})$ need not be ordinary *sentenças* of first-order logic, in this chapter we use *variáveis* $\alpha, \beta, \dots$ to range over them, and reserve $\varphi, \psi, \dots$ for ordinary first-order *fórmulas*.

Definição 4.2. Let $\text{Mod}_L(\alpha)$ denote the class $\{\mathfrak{M} : \mathfrak{M} \models_L \alpha\}$. If the *linguagem* needs to be made explicit, we write $\text{Mod}_L^{\mathcal{L}}(\alpha)$. Two *estruturas* $\mathfrak{M}$ and $\mathfrak{N}$ for $\mathcal{L}$ are *elementarily equivalent* in $\langle L, \models_L \rangle$, written $\mathfrak{M} \equiv_L \mathfrak{N}$, if the same *sentenças* from $L(\mathcal{L})$ are true in each.

Definição 4.3. An abstract logic $\langle L, \models_L \rangle$ for the *linguagem* $\mathcal{L}$ is *normal* if it satisfies the following properties:

1. (*L-Monotonicity*) For *linguagens* $\mathcal{L}$ and $\mathcal{L}'$, if $\mathcal{L} \subseteq \mathcal{L}'$, then $L(\mathcal{L}) \subseteq L(\mathcal{L}')$.
2. (*Expansion Property*) For each $\alpha \in L(\mathcal{L})$ there is a *finite* subset $\mathcal{L}'$ of $\mathcal{L}$ such that the relation $\mathfrak{M} \models_L \alpha$ depends only on the reduct of $\mathfrak{M}$ to $\mathcal{L}'$; O.s., if $\mathfrak{M}$ and $\mathfrak{N}$ have the same reduct to $\mathcal{L}'$ then $\mathfrak{M} \models_L \alpha$ if and only if $\mathfrak{N} \models_L \alpha$.
3. (*Isomorphism Property*) If $\mathfrak{M} \models_L \alpha$ and $\mathfrak{M} \simeq \mathfrak{N}$ then also $\mathfrak{N} \models_L \alpha$.
4. (*Renaming Property*) The relation $\models_L$ is preserved under renaming: if the *linguagem* $\mathcal{L}'$ is obtained from $\mathcal{L}$ by replacing each symbol P by a symbol P' of the same arity and each constant c by a distinct constant c' , then for each *estrutura* $\mathfrak{M}$ and *sentença* α , $\mathfrak{M} \models_L \alpha$ if and only if $\mathfrak{M}' \models_L \alpha'$, where $\mathfrak{M}'$ is the $\mathcal{L}'$ -*estrutura* corresponding to $\mathfrak{M}$ and $\alpha' \in L(\mathcal{L}')$.
5. (*Boolean Property*) The abstract logic $\langle L, \models_L \rangle$ is closed under the Boolean connectives in the sense that for each $\alpha \in L(\mathcal{L})$ there is a $\beta \in L(\mathcal{L})$ such that $\mathfrak{M} \models_L \beta$ if and only if $\mathfrak{M} \not\models_L \alpha$, and for each α and β there is a γ such that $\text{Mod}_L(\gamma) = \text{Mod}_L(\alpha) \cap \text{Mod}_L(\beta)$. Similarly for atomic *fórmulas* and the other connectives.
6. (*Quantifier Property*) For each constant c in $\mathcal{L}$ and $\alpha \in L(\mathcal{L})$ there is a $\beta \in L(\mathcal{L})$ such that

$$\text{Mod}_L^{\mathcal{L}'}(\beta) = \{\mathfrak{M} : (\mathfrak{M}, a) \in \text{Mod}_L^{\mathcal{L}}(\alpha) \text{ for some } a \in |\mathfrak{M}|\},$$

where $\mathcal{L}' = \mathcal{L} \setminus \{c\}$ and $(\mathfrak{M}, a)$ is the expansion of $\mathfrak{M}$ to $\mathcal{L}$ assigning a to c .

7. (*Relativization Property*) Given a *sentença* $\alpha \in L(\mathcal{L})$ and symbols $R, c_1, \dots, c_n$ not in $\mathcal{L}$, there is a *sentença* $\beta \in L(\mathcal{L} \cup \{R, c_1, \dots, c_n\})$ called the *relativization* of α to $R(x, c_1, \dots, c_n)$, such that for each *estrutura* $\mathfrak{M}$:

$$(\mathfrak{M}, X, b_1, \dots, b_n) \models_L \beta \text{ if and only if } \mathfrak{N} \models_L \alpha,$$

where $\mathfrak{N}$ is the substructure of $\mathfrak{M}$ with *domínio* $|\mathfrak{N}| = \{a \in |\mathfrak{M}| : R^{\mathfrak{M}}(a, b_1, \dots, b_n)\}$ (see *Observação 1*), and $(\mathfrak{M}, X, b_1, \dots, b_n)$ is the expansion of $\mathfrak{M}$ interpreting $R, c_1, \dots, c_n$ by $X, b_1, \dots, b_n$, respectively (with $X \subseteq M^{n+1}$).

Definição 4.4. Given two abstract logics $\langle L_1, \models_{L_1} \rangle$ and $\langle L_2, \models_{L_2} \rangle$ we say that the latter is *at least as expressive* as the former, written $\langle L_1, \models_{L_1} \rangle \leq \langle L_2, \models_{L_2} \rangle$, if for each **linguagem** $\mathcal{L}$ and **sentença** $\alpha \in L_1(\mathcal{L})$ there is a **sentença** $\beta \in L_2(\mathcal{L})$ such that $\text{Mod}_{L_1}^{\mathcal{L}}(\alpha) = \text{Mod}_{L_2}^{\mathcal{L}}(\beta)$. The logics $\langle L_1, \models_{L_1} \rangle$ and $\langle L_2, \models_{L_2} \rangle$ are *equivalent* if $\langle L_1, \models_{L_1} \rangle \leq \langle L_2, \models_{L_2} \rangle$ and $\langle L_2, \models_{L_2} \rangle \leq \langle L_1, \models_{L_1} \rangle$.

Observação 5. First-order logic, O.s., the abstract logic $\langle F, \models \rangle$, is normal. In fact, the above properties are mostly straightforward for first-order logic. We just remark that the expansion property comes down to extensionality, and that the relativization of a **sentença** α to $R(x, c_1, \dots, c_n)$ is obtained by replacing each **subfórmula** $\forall x \beta$ by $\forall x (R(x, c_1, \dots, c_n) \rightarrow \beta)$. Moreover, if $\langle L, \models_L \rangle$ is normal, then $\langle F, \models \rangle \leq \langle L, \models_L \rangle$, as can be shown by induction on first-order **fórmulas**. Accordingly, with no loss in generality, we can assume that every first-order **sentença** belongs to every normal logic.

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4.3 Compactness and Löwenheim–Skolem Properties

We now give the obvious extensions of compactness and Löwenheim–Skolem to the case of abstract logics. mod:lin:lsp:
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Definição 4.5. An abstract logic $\langle L, \models_L \rangle$ has the *Compactness Property* if each set Γ of $L(\mathcal{L})$ -**sentenças** is satisfiable whenever each finite $\Gamma_0 \subseteq \Gamma$ is satisfiable.

Definição 4.6. $\langle L, \models_L \rangle$ has the *Downward Löwenheim–Skolem property* if any satisfiable Γ has a **enumerável** model.

The notion of partial isomorphism from **Definição 1.15** is purely “algebraic” (O.s., given without reference to the **sentenças** of the language but only to the constants provided by the **linguagem** $\mathcal{L}$ of the **estruturas**), and hence it applies to the case of abstract logics. In case of first-order logic, we know from **Teorema 1.17** that if two **estruturas** are partially isomorphic then they are elementarily equivalent. That proof does not carry over to abstract logics, for induction on **fórmulas** need not be available for arbitrary $\alpha \in L(\mathcal{L})$, but the theorem is true nonetheless, provided the Löwenheim–Skolem property holds.

Teorema 4.7. Suppose $\langle L, \models_L \rangle$ is a normal logic with the Löwenheim–Skolem property. Then any two **estruturas** that are partially isomorphic are elementarily equivalent in $\langle L, \models_L \rangle$. mod:lin:lsp:
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Prova. Suppose $\mathfrak{M} \simeq_p \mathfrak{N}$, but for some α also $\mathfrak{M} \models_L \alpha$ while $\mathfrak{N} \not\models_L \alpha$. By the Isomorphism Property we can assume that $|\mathfrak{M}|$ and $|\mathfrak{N}|$ are disjoint, and by the Expansion Property we can assume that $\alpha \in L(\mathcal{L})$ for a finite **linguagem** $\mathcal{L}$. Let $\mathcal{I}$ be a set of partial isomorphisms between $\mathfrak{M}$ and $\mathfrak{N}$, and with no loss of generality also assume that if $p \in \mathcal{I}$ and $q \subseteq p$ then also $q \in \mathcal{I}$.

$|\mathfrak{M}|^{<\omega}$ is the set of finite sequences of **membros** of $|\mathfrak{M}|$. Let S be the ternary relation over $|\mathfrak{M}|^{<\omega}$ representing concatenation, O.s., if $\mathbf{a}, \mathbf{b}, \mathbf{c} \in |\mathfrak{M}|^{<\omega}$ then $S(\mathbf{a}, \mathbf{b}, \mathbf{c})$ holds if and only if $\mathbf{c}$ is the concatenation of $\mathbf{a}$ and $\mathbf{b}$; and let T be the ternary relation such that $T(\mathbf{a}, b, \mathbf{c})$ holds for $b \in M$ and $\mathbf{a}, \mathbf{c} \in |\mathfrak{M}|^{<\omega}$ if and only if $\mathbf{a} = a_1, \dots, a_n$ and $\mathbf{c} = a_1, \dots, a_n, b$. Pick new 3-place **símbolos de predicado** P and Q and form the **estrutura** $\mathfrak{M}^*$ having the universe $|\mathfrak{M}| \cup |\mathfrak{M}|^{<\omega}$, having $\mathfrak{M}$ as a substructure, and interpreting P and Q by the concatenation relations S and T (so $\mathfrak{M}^*$ is in the **linguagem** $\mathcal{L} \cup \{P, Q\}$).

Define $|\mathfrak{N}|^{<\omega}$, S' , T' , P' , Q' and $\mathfrak{N}^*$ analogously. Since by hypothesis $\mathfrak{M} \simeq_p \mathfrak{N}$, there is a relation I between $|\mathfrak{M}|^{<\omega}$ and $|\mathfrak{N}|^{<\omega}$ such that $I(\mathbf{a}, \mathbf{b})$ holds if and only if $\mathbf{a}$ and $\mathbf{b}$ are isomorphic and satisfy the back-and-forth condition of **Definição 1.15**. Now, let $\mathfrak{M}$ be the **estrutura** whose **domínio** is the union of the **domínios** of $\mathfrak{M}^*$ and $\mathfrak{N}^*$, having $\mathfrak{M}^*$ and $\mathfrak{N}^*$ as **subestruturas**, in the **linguagem** with one extra binary **símbolo de predicado** R interpreted by the relation I and **símbolos de predicado** denoting the **domínios** $|\mathfrak{M}|^*$ and $|\mathfrak{N}|^*$.

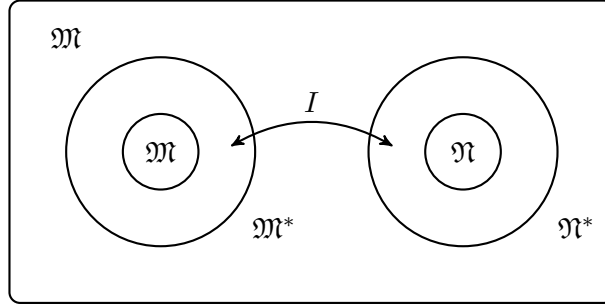


Figura 4.1: The **estrutura** $\mathfrak{M}$ with the internal partial isomorphism.

The crucial observation is that in the **linguagem** of the **estrutura** $\mathfrak{M}$ there is a *first-order* **sentença** θ_1 true in $\mathfrak{M}$ saying that $\mathfrak{M} \models_L \alpha$ and $\mathfrak{N} \not\models_L \alpha$ (this requires the Relativization Property), as well as a *first-order* **sentença** θ_2 true in $\mathfrak{M}$ saying that $\mathfrak{M} \simeq_p \mathfrak{N}$ via the partial isomorphism I . By the Löwenheim–Skolem Property, θ_1 and θ_2 are jointly true in a **enumerável** model $\mathfrak{M}_0$ containing partially isomorphic substructures $\mathfrak{M}_0$ and $\mathfrak{N}_0$ such that $\mathfrak{M}_0 \models_L \alpha$ and $\mathfrak{N}_0 \not\models_L \alpha$. But **enumerável** partially isomorphic **estruturas** are in fact isomorphic by **Teorema 1.16**, contradicting the Isomorphism Property of normal abstract logics. $\square$

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4.4 Lindström’s Theorem

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Lema 4.8. Suppose $\alpha \in L(\mathcal{L})$, with $\mathcal{L}$ finite, and assume also that there is an $n \in \mathbb{N}$ such that for any two **estruturas** $\mathfrak{M}$ and $\mathfrak{N}$, if $\mathfrak{M} \equiv_n \mathfrak{N}$ and $\mathfrak{M} \models_L \alpha$

then also $\mathfrak{N} \models_L \alpha$. Then α is equivalent to a first-order *sentença*, O.s., there is a first-order θ such that $\text{Mod}_L(\alpha) = \text{Mod}_L(\theta)$.

Prova. Let n be such that any two n -equivalent *estruturas* $\mathfrak{M}$ and $\mathfrak{N}$ agree on the value assigned to α . Recall **Proposição 1.19**: there are only finitely many first-order *sentenças* in a finite *linguagem* that have quantifier rank no greater than n , up to logical equivalence. Now, for each fixed *estrutura* $\mathfrak{M}$ let $\theta_{\mathfrak{M}}$ be the conjunction of all first-order *sentenças* α true in $\mathfrak{M}$ with $\text{qr}(\alpha) \leq n$ (this conjunction is finite), so that $\mathfrak{N} \models \theta_{\mathfrak{M}}$ if and only if $\mathfrak{N} \equiv_n \mathfrak{M}$. Then put $\theta = \bigvee \{\theta_{\mathfrak{M}} : \mathfrak{M} \models_L \alpha\}$; this disjunction is also finite (up to logical equivalence).

The conclusion $\text{Mod}_L(\alpha) = \text{Mod}_L(\theta)$ follows. In fact, if $\mathfrak{N} \models_L \theta$ then for some $\mathfrak{M} \models_L \alpha$ we have $\mathfrak{N} \models \theta_{\mathfrak{M}}$, whence also $\mathfrak{N} \models_L \alpha$ (by the hypothesis of the lemma). Conversely, if $\mathfrak{N} \models_L \alpha$ then $\theta_{\mathfrak{N}}$ is a disjunct in θ , and since $\mathfrak{N} \models \theta_{\mathfrak{N}}$, also $\mathfrak{N} \models_L \theta$. $\square$

Teorema 4.9 (Lindström's Theorem). *Suppose $\langle L, \models_L \rangle$ has the Compactness and the Löwenheim–Skolem Properties. Then $\langle L, \models_L \rangle \leq \langle F, \models \rangle$ (so $\langle L, \models_L \rangle$ is equivalent to first-order logic).*

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Prova. By **Lema 4.8**, it suffices to show that for any $\alpha \in L(\mathcal{L})$, with $\mathcal{L}$ finite, there is $n \in \mathbb{N}$ such that for any two *estruturas* $\mathfrak{M}$ and $\mathfrak{N}$: if $\mathfrak{M} \equiv_n \mathfrak{N}$ then $\mathfrak{M}$ and $\mathfrak{N}$ agree on α . For then α is equivalent to a first-order *sentença*, from which $\langle L, \models_L \rangle \leq \langle F, \models \rangle$ follows. Since we are working in a finite, purely relational *linguagem*, by **Teorema 1.23** we can replace the statement that $\mathfrak{M} \equiv_n \mathfrak{N}$ by the corresponding algebraic statement that $I_n(\emptyset, \emptyset)$.

Given α , suppose towards a contradiction that for each n there are *estruturas* $\mathfrak{M}_n$ and $\mathfrak{N}_n$ such that $I_n(\emptyset, \emptyset)$, but (say) $\mathfrak{M}_n \models_L \alpha$ whereas $\mathfrak{N}_n \not\models_L \alpha$. By the Isomorphism Property we can assume that all the $\mathfrak{M}_n$'s interpret the constants of the language by the same objects; furthermore, since there are only finitely many atomic *sentenças* in the language, we may also assume that they satisfy the same atomic *sentenças* (we can take a subsequence of the $\mathfrak{M}$'s otherwise). Let $\mathfrak{M}$ be the union of all the $\mathfrak{M}_n$'s, O.s., the unique minimal *estrutura* having each $\mathfrak{M}_n$ as a substructure. As in the proof of **Teorema 4.7**, let $\mathfrak{M}^*$ be the extension of $\mathfrak{M}$ with *domínio* $|\mathfrak{M}| \cup |\mathfrak{M}|^{<\omega}$, in the expanded *linguagem* comprising the concatenation predicates P and Q .

Similarly, define $\mathfrak{N}_n$, $\mathfrak{N}$ and $\mathfrak{N}^*$. Now let $\mathfrak{M}$ be the *estrutura* whose *domínios* comprises the *domínios* of $\mathfrak{M}^*$ and $\mathfrak{N}^*$ as well as the natural numbers $\mathbb{N}$ along with their natural ordering $\leq$, in the *linguagem* with extra predicates representing the *domínios* $|\mathfrak{M}|$, $|\mathfrak{N}|$, $|\mathfrak{M}|^{<\omega}$ and $|\mathfrak{N}|^{<\omega}$ as well as predicates coding the domains of $\mathfrak{M}_n$ and $\mathfrak{N}_n$ in the sense that:

$$\begin{aligned} |\mathfrak{M}_n| &= \{a \in |\mathfrak{M}| : R(a, n)\}; & |\mathfrak{N}_n| &= \{a \in |\mathfrak{N}| : S(a, n)\}; \\ |\mathfrak{M}|_n^{<\omega} &= \{a \in |\mathfrak{M}|^{<\omega} : R(a, n)\}; & |\mathfrak{N}|_n^{<\omega} &= \{a \in |\mathfrak{N}|^{<\omega} : S(a, n)\}. \end{aligned}$$

The *estrutura* $\mathfrak{M}$ also has a ternary relation J such that $J(n, \mathbf{a}, \mathbf{b})$ holds if and only if $I_n(\mathbf{a}, \mathbf{b})$.

Now there is a *sentença* θ in the *linguagem* $\mathcal{L}$ augmented by R, S, J , etc., saying that $\leq$ is a discrete linear ordering with first but no last element and such that $\mathfrak{M}_n \models \alpha$, $\mathfrak{N}_n \not\models \alpha$, and for each n in the ordering, $J(n, \mathbf{a}, \mathbf{b})$ holds if and only if $I_n(\mathbf{a}, \mathbf{b})$.

Using the Compactness Property, we can find a model $\mathfrak{M}^*$ of θ in which the ordering contains a non-standard element n^* . In particular then $\mathfrak{M}^*$ will contain subestruturas $\mathfrak{M}_{n^*}$ and $\mathfrak{N}_{n^*}$ such that $\mathfrak{M}_{n^*} \models_L \alpha$ and $\mathfrak{N}_{n^*} \not\models_L \alpha$. But now we can define a set $\mathcal{I}$ of pairs of k -tuples from $|\mathfrak{M}_{n^*}|$ and $|\mathfrak{N}_{n^*}|$ by putting $\langle \mathbf{a}, \mathbf{b} \rangle \in \mathcal{I}$ if and only if $J(n^* - k, \mathbf{a}, \mathbf{b})$, where k is the length of $\mathbf{a}$ and $\mathbf{b}$. Since n^* is non-standard, for each standard k we have that $n^* - k > 0$, and the set $\mathcal{I}$ witnesses the fact that $\mathfrak{M}_{n^*} \simeq_p \mathfrak{N}_{n^*}$. But by *Teorema 4.7*, $\mathfrak{M}_{n^*}$ is L -equivalent to $\mathfrak{N}_{n^*}$, a contradiction. $\square$

Créditos das Imagens

Referências Bibliográficas