21603 Model Theory I

Rohan Jain

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Chapter 1

1.1 random info

rami@cmu.edu

1. Set Theory
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1973 book by Chang and Keisler - Model Theory - Highly recommended for elementary model theory.
What is model thoery? Model Theory = logic + universal algebra
1984 - W. Hodges - Shorter Model Theory
model theory = algebraic geometry - field theory
Algebraic structures:

1. groups
2. rings
3. vector spaces
4. fields
5. graphs - (V, E)
6. ordered structures

Around 1870, mathematicians started to layout the foundations for mathematics. One of the ideas was axiomatization. One example was Euclidean axioms for plane geometry.

1.2 Structures and Languages

Definition 1.2.1: Language

L is a language if $L = F \cup R \cup C$ are parameter disjoint.

Definition 1.2.2: L-structure

Let L be a language (similarity type/signature). Then $\mathcal{M}$ is an L-structure provided:

$$\mathcal{M} = (U, \{f^{\mathcal{M}} \mid f \in F\}, \{r^{\mathcal{M}} \mid r \in R\}, \{c^{\mathcal{M}} \mid c \in C\})$$

where U is a nonempty set. U is also called the universe of $\mathcal{M}$.
For any $f \in F$ there is $U(f)$ natural number such that $f^{\mathcal{M}} : U^{n(F)} \to U$, $R^{\mathcal{M}} \subseteq U^{n(R)}$, $C^{\mathcal{M}} \subseteq U$, $\forall c \in C$.

Notation: $|\mathcal{M}| = U$. The cardinal of $\mathcal{M}$ is $|U|$. $\|\mathcal{M}\|$ denotes the cardinality of $\mathcal{M}$.

Definition 1.2.3: Theory

Let L be a language. A theory T is a set of sentences in L. A sentence is a finite set of symbols from L.

Example 1.2.1 (Sentences)
$L_{\text{gr}} = \{e, \cdot\}$. $e \in C$, $\cdot \in F$. $T_{\text{gr}} = \{\forall x \forall y \forall z (x \cdot (y \cdot z) = (x \cdot y) \cdot z), \forall x (x \cdot e = x, e \cdot x = x), \forall x \exists y (x \cdot y = e, y \cdot x = e)\}$. These are the group axioms (associativity, identity, existence of inverse).

Definition 1.2.4: Term

Let L be a language. A term is:

1. c is a term for any $c \in C$.
2. x when x is a variable.
3. $\tau_1, \ldots, \tau_k$ terms, $f \in F$, $n(f) = k$, then $f(\tau_1, \ldots, \tau_k)$ is a term.

Definition 1.2.5: Term

Term(L) is a minimal set of finite strings of symbols from $L \cup \{(,)\} \cup X$ that contains $C \cup x$ and closed under the following rule:

$$\tau_1, \ldots, \tau_k \in \text{Term}(L), f k-\text{place function symbol, then} f(\tau_1, \ldots, \tau_k) \in \text{Term}(L)$$

Example 1.2.2 (L_r)
$L_r = \{0, 1, +, -\}$. $\text{Term}(L_r) \supseteq \{\sum a_j x_1^{n_j} \mid a_j \in \mathbb{Z}, n_j \in \mathbb{N}\}$.

Example 1.2.3 (L_{gr})
$\text{Term}(L_{\text{gr}}) \supseteq \{x_1 \cdot x_n \cdots x_n \mid x_i \in X, n \in \omega\}$.

Definition 1.2.6: AFml

Let L be a language. The set of atomic fomrulas denotes by AFml(L) is the smallest set of formulas in L that contains $L \cup \{(,), =\} \cup X$ such that:

1. If $\tau_1, \tau_2 \in \text{Term}(L)$, then $\tau_1 = \tau_2 \in \text{AFml}(L)$.
2. Given $R(x_1, \ldots, x_n)$ relation symbol and $\tau_1, \ldots, \tau_n \in \text{Term}(L)$, then $R(\tau_1, \ldots, \tau_n) \in \text{AFml}(L)$.

Definition 1.2.7: Fml

$\mathrm{Fml}(L)$ is the set of (first order) formulas in L. Which is the mininmal set of finite strings of symbols from $L \cup \{(,), =, \neg, \vee, \wedge, \implies, \impliedby, \iff, \forall, \exists\} \cup X$ such that:

1. $\mathrm{Fml}(L) \supseteq \mathrm{AFml}(L)$.
2. If φ is a formula, then $\neg\varphi$ is a formula.
3. If $x \in \{\wedge, \vee, \implies, \iff\}$ and $\varphi, \psi \in \mathrm{Fml}(L)$, then $(\varphi x \psi) \in \mathrm{Fml}(L)$.
4. If $\varphi \in \mathrm{Fml}(L)$, $Q \in \{\forall, \exists\}$, and $x \in X$, then $Qx\varphi \in \mathrm{Fml}(L)$.
5. If $\varphi \in \mathrm{Fml}(L)$, $\mathrm{FV}(\varphi)$ is the set of free variables in φ defined by induction on the structure of φ.
   Case 1: $\varphi \in \mathrm{AFml}(L)$.
   (a) φ is $\tau_1 = \tau_2$. $\mathrm{FV}(\varphi) = \mathrm{FV}(\tau_1) \cup \mathrm{FV}(\tau_2)$.
   (b) φ is $R(\tau_1, \dots, \tau_n)$. $\mathrm{FV}(\varphi) = \mathrm{FV}(\tau_1) \cup \dots \cup \mathrm{FV}(\tau_n)$.

   Case 2:
   (a) if φ is $\neg\psi$, then $\mathrm{FV}(\varphi) = \mathrm{FV}(\psi)$.
   (b) if $\varphi = \psi_1 * \psi_2$ for $* \in \{\wedge, \vee, \implies, \iff\}$, then $\mathrm{FV}(\varphi) = \mathrm{FV}(\psi_1) \cup \mathrm{FV}(\psi_2)$.

   Case 3: φ is $Qx\psi$, $Q \in \{\forall, \exists\}$. Then $\mathrm{FV}(\varphi) = \mathrm{FV}(\psi) \setminus \{x\}$.
6. $\mathrm{Sent}(L)$ are the sentences in L. $\mathrm{Sent}(L) = \{\varphi \in \mathrm{Fml}(L) \mid \mathrm{FV}(\varphi) = \emptyset\}$.

Example 1.2.4

If $L_f = \{+, \cdot, 0, 1\}$, then $T_f = \{$

- $\forall x \forall y \forall z (x \cdot (y \cdot z) = (x \cdot y) \cdot z)$,
- $\forall x \forall y \forall z (x + (y + z) = (x + y) + z)$,
- $\forall x \forall y (x + y = y + x)$,
- $\forall x \forall y (x \cdot y = y \cdot x)$,
- $\forall x (x \cdot 1 = x, 1 \cdot x = x)$,
- $\forall x (x + 0 = x, 0 + x = x)$,
- $\forall x \exists y (x \cdot y = 1, y \cdot x = 1)$,
- $\forall x \exists y (x + y = 0, y + x = 0)$,
- $\forall x \forall y \forall z (x \cdot (y + z) = (x \cdot y) + (x \cdot z))$

$\}$.

Definition 1.2.8: L-theory

T is an L-theory if $T \subseteq \mathrm{Sent}(L)$.

The example above is "field theory".

Definition 1.2.9

Let M be an L-structure. $\tau(\bar{x})$ is a term, $\bar{a} \in |M|^{\ell(n)}$. T
Case 1: $\tau(\bar{x}) = c$ for some constant symbol. Then $\tau^M(\bar{a}) = c^M$.
Case 2: $\tau(\bar{x}) = x_i$. Then $\tau^M(\bar{a}) = a_i$.
Case 3: $\tau(\bar{x}) = f(\tau_1, \ldots, \tau_k)$. Then $\tau^M(\bar{a}) = f^M(\tau_1^M(\bar{a}), \ldots, \tau_k^M(\bar{a}))$.

Definition 1.2.10: $\models$

Let L be a language, $\varphi \in \mathrm{Fml}(L)$, M and L-structure, $n = \ell(\bar{x})$, $\bar{a} \in |M|^n$. Define $M \models \varphi(\bar{a})$ at $\bar{a}$ by induction on the structure of φ:

- If φ is atomic,
  - when $\varphi(x)$ is $\tau_1 = \tau_2$, then $M \models \varphi(\bar{a})$ iff $\tau_1(\bar{a}) = \tau_2(\bar{a})$.
  - when $\varphi(x)$ is $R(\tau_1, \ldots, \tau_k)$, then $M \models \varphi(\bar{a})$ iff $(\tau_1(\bar{a}), \ldots, \tau_k(\bar{a})) \in R^M$.
- If φ is not atomic, then:
  - if φ is $\neg\psi$, then $M \models \varphi(\bar{a})$ iff $M \models \psi(\bar{a})$ is false.
  - if φ is $\psi_1 * \psi_2$ for $* \in \{\wedge, \vee, \implies, \iff\}$, then $M \models \varphi(\bar{a})$ iff $M \models \psi_1(\bar{a})$ and $M \models \psi_2(\bar{a})$.
  - if φ is $\exists y \psi(y, \bar{x})$, then $M \models \varphi(\bar{a})$ iff there is $b \in |M|$ such that $M \models \psi(b, \bar{a})$.
  - if φ is $\forall y \psi(y, \bar{x})$, then $M \models \varphi(\bar{a})$ iff for all $b \in |M|$, $M \models \psi(b, \bar{a})$.

Definition 1.2.11

Let M be an L-structure and T an L-theory. $M \models T$ iff for every $\varphi \in T$, $M \models \varphi$. We say T "satisfies" M.

Example 1.2.5 (Models)
$M \models T_f \iff (|M|, +^M, \cdot^M, 0^M, 1^M)$ is a field.

Definition 1.2.12: Mod

$\mathrm{Mod}(T) = \{M \text{ } L\text{-structure} \mid M \models T\}$.

Example 1.2.6
$\mathrm{Mod}(T_f)$ is the class of all fields and $\mathrm{Mod}(T_{\mathrm{gr}})$ is the class of all groups.

Definition 1.2.13: Structure Isomorphism

Let M, N both be L-structures. f is an isomorphism from M onto N if $f : |M| \to |N|$ is a bijection such that:

- $f(c^M) = c^N$ for all $c \in C$.
- $G(x_1, \ldots, x_k)$ function symbol. $a_1, \ldots, a_k \in |M|$, then $f(G^M(a_1, \ldots, a_k)) = G^N(f(a_1), \ldots, f(a_k))$.
- $R(x_1, \ldots, x_k)$ predicate symbol. $a_1, \ldots, a_k \in |M|$, then $(a_1, \ldots, a_k) \in R^M$ iff $(f(a_1), \ldots, f(a_k)) \in R^N$.

We write $f : M \cong N$. Also $M \cong N \iff \exists f : M \cong N$.

Definition 1.2.14

Let $\lambda \geqslant \aleph_0$, T an L-theory. T is λ-categorical if for all $M, N \models T$ of cardinality λ, $M \cong N$.

Theorem 1.2.1 Los Conjecture (1954)

Let L be a language, T a first order L-theory, in an at most countable language. If $\exists \lambda > \aleph_0$ such that T is λ-categorical, then for all $\mu > \aleph_0$, T is μ-categorical.

Somewhere around 1961-1965, Morley proved this conjecture.

Chapter 2

Basic Concepts

Lenma 2.0.1

1. $M \cong N \implies N \cong M$.
2. $M \cong M$, $f = \mathrm{id}_{|M|}$.
3. Let M_1, M_2, M_3 be all L-structures. Then $f_1 : M_1 \cong M_2$ and $f_2 : M_2 \cong M_3 \implies f_2 \circ f_1 : M_1 \cong M_3$.

In other words, $\cong$ is an equivalence relation on $\mathrm{Struct}(L)$.

$M/\cong = \{N \text{ is an } L(M)\text{-structure} \mid N \cong M\}$.

Definition 2.0.1: Spectrum function of T

Let T be a first order theory ($T \subseteq \mathrm{Sent}(L)$) of cardinality λ. Then $I(\lambda, T)$ is the number of pairwise nonisomorphic models of T of cardinality λ. We have

$$I(\lambda, T) = |M/\cong|$$

where $M \models T$ and $\|M\| = \lambda$.

Consider $\lambda \mapsto I(\lambda, T)$, $\lambda \in \mathrm{Card}$ (the class of cardinal numbers). But what is the shape of $\lambda \mapsto I(\lambda, T)$. Is it weakly monotone? That is, $\mu > \lambda \implies I(\mu, T) \geqslant I(\lambda, T)$?

Theorem 2.0.1 Morley's Conjecture (~1965)

Suppose T is first order and $|L(T)| \leqslant \aleph_0$. Then $\mu > \lambda > \aleph_0 \implies I(\mu, T) \geqslant I(\lambda, T)$.

The basic problem is that given M and N both of cardinality λ, $M \ncong N$, find M', N' both of cardinality μ such that $M' \cong N'$. In 1990, Shelah solved Morley's Conjecture. However, this is an open question for uncountable T.

Theorem 2.0.2 Morley's Category Theorem

Let T be a first order theory for $|L(T)| \leqslant \aleph_0$. Then $\exists \lambda > \aleph_0, I(\lambda, T) = 1$ then $\forall \mu > \aleph_0$, $I(\mu, T) = 1$.

Shelah listed all possible functions $\lambda \mapsto I(\lambda, T)$ and, by hand, verified that they were weakly monotone.

Example 2.0.1

1. $I(\lambda, T) = 1$ for all $\lambda > \aleph_0$.
2. $I(\lambda, T) = 2^\lambda$ for all $\lambda > \aleph_0$.

Hart, Hrushovski, and Laskowski found all the 13 functions.

Definition 2.0.2: Submodel

Let M, N be L-structures. M is a submodel of N if:

1. $|M| \leqslant |N|$
2. $\forall a_1, \ldots, a_n \in |M|$ and $F(x_1, \ldots, x_n)$, $F^M(a_1, \ldots, a_n) = F^N(a_1, \ldots, a_n)$.
3. $c^M = c^N$ for all constant symbols c.
4. $R^M = R^N \cap (|M| \times \cdots \times |M|)$.

Definition 2.0.3: Elementarily Equivalent

Let M, N be L-structure. M is elementarily equivalent to N denoted by $M \equiv N$ provided $M \models \varphi \iff N \models \varphi$ for any $\varphi \in \mathrm{Sent}(L)$.

Definition 2.0.4

Let M be an L-structure. The theory of M is denoted $(M) = \{\mathrm{Th}(M)\varphi \in \mathrm{Sent}(L) \mid M \models \varphi\}$.

Let $N := (\omega, +, \cdot, 0, 1)$. Then $\mathrm{TA} = \mathrm{Th}(N)$ "True Arithmetic". For example the twin primes conjecture is $\{p \mid p$ and $p+2$ are both primes$\}$ is infinite. If it is true, then it is a member of TA.

Theorem 2.0.3

Let M, N be L-stuructres. If $M \cong N$, then $M \equiv N$.

Theorem 2.0.4

Let M, N be L-structures. Suppose $f : M \cong N$. Then for any $\bar{a} \in |M|$ and any $\varphi(\bar{x}) \in \mathrm{Fml}(L)$ with $\ell(\bar{x}) = \ell(\bar{a})$, $M \models \varphi[\bar{a}] \iff N \models \varphi[f(\bar{a})]$.

Proof. Suppose $\varphi(\bar{x})$ is atomic.

Lenma 2.0.2

Suppose $f : M \cong N$ and $\tau(\bar{x})$ sequence of terms. $\bar{a} \in |M|$, $\ell(\bar{x}) = \ell(\bar{a})$. Then $f(\tau(\bar{a})) = \tau(f(\bar{a}))$.

Proof. By induction on the length of τ.

Case 1: $\tau(\bar{x})$ is x. Then $f(\tau(\bar{a})) = f(a) = \tau(f(\bar{a}))$.

Case 2: $\tau(\bar{x}) = c$. then $f(c^M) = c^N$ by definition of isomorphism.

Case 3: $\tau(\bar{x}) = G(y_1, \ldots, y_n)$ function symbol. Then $\tau_1(\bar{x}), \ldots, \tau_n(\bar{x})$ are terms. By induction, $f(\tau(\bar{a})) = f(G^M(\tau_1(\bar{a}), \ldots, \tau_n(\bar{a}))) = G^N(f(\tau_1(\bar{a})), \ldots, f(\tau_n(\bar{a}))) = \tau^N(f(\bar{a}))$. 😊

Now returning to the proof:

Case 1: $\varphi(\bar{x})$ is $\tau_1(\bar{x}) = \tau_2(\bar{x})$. Then, we have $M \models \varphi(\bar{a}) \iff \tau_1(\bar{a}) = \tau_2(\bar{a}) \iff f(\tau_1(\bar{a})) = f(\tau_2(\bar{a})) \iff \tau_1^N(f(\bar{a})) = \tau_2^N(f(\bar{a})) \iff N \models \varphi(f(\bar{a}))$.

Case 2: $\varphi(\bar{x})$ is $R(\tau_1(\bar{x}), \ldots, \tau_n(\bar{x}))$. When $R(y_1, \ldots, y_n)$ is a relation symbol and $\tau_i(\bar{x})$ are terms. Then $M \models \varphi(\bar{a}) \iff (\tau_1(\bar{a}), \ldots, \tau_n(\bar{a})) \in R^M \iff (f(\tau_1(\bar{a})), \ldots, f(\tau_n(\bar{a}))) \in R^N \iff (\tau_1(f(\bar{a})), \ldots, \tau_n(f(\bar{a}))) \iff N \models \varphi(f(\bar{a}))$.

Suppose φ is $\neg\psi$. Then $M \models \varphi(\bar{a}) \iff M \not\models \psi(\bar{a}) \iff N \not\models \psi(f(\bar{a})) \iff N \models \varphi(f(\bar{a}))$.

Suppose φ is $\psi_1 \wedge \psi_2$. Then $M \models \varphi(\bar{a}) \iff M \models \psi_1(\bar{a})$ and $M \models \psi_2(\bar{a}) \iff N \models \psi_1(f(\bar{a}))$ and $N \models \psi_2(f(\bar{a})) \iff N \models \varphi(f(\bar{a}))$.

Suppose $\varphi(\bar{x})$ is $\exists y \psi(y, \bar{x})$. Then $M \models \varphi(\bar{a}) \iff$ there is $b \in |M|$ such that $M \models \psi(b, \bar{a}) \iff$ there is $c \in |N|$ such that $N \models \psi(c, f(\bar{a})) \iff N \models \exists\psi(y, f(\bar{a})) \iff N \models \varphi(f(\bar{a}))$. 😊

General Remark:

$$M \models \exists y \varphi(y, \bar{a}) \iff M \models \neg \forall y \neg \varphi(y, \bar{a})$$
$$M \models \neg \exists y \varphi(y, \bar{x}) \iff \forall y \neg \varphi(y, \bar{a}).$$

Example 2.0.2

$L_{gr} = \{\cdot, 1\}$. $(\mathbb{Q}, +, 0), (\mathbb{R}, +, 0)$ are not isomorphic because diff cardinality. $(\mathbb{Q}, +, 0), (\mathbb{Z}, +, 0)$ are not isomorphic because:

$$(\mathbb{Q}, +, 0) \models \forall x \exists y (x = y + y).$$

This sentence is not true for $\mathbb{Z}$ under addition.

$N = (\omega, +, \cdot, 0, 1)$ is called the standard model of arithmetic. TA = Th(N), true arithmetic.

Question

Given $M_1, M_2 \models$ TA both countable. Are they isomorphic?

Question

What is $I(\aleph_0, \mathrm{TA})$? Voted on $2^{\aleph_0}$.... and it is.

Let T be a theory and $\varphi \in \mathrm{Sent}(L)$. We say T proves φ (denoted $T \vdash \varphi$) if there exists a finite set of sequences from L, $\varphi_1, \varphi_2, \ldots, \varphi_n$ such that $\varphi_n = \varphi$ and for all i, $\varphi_i \in T$ or φ_i is a tautology or there are $j, k < i$ where $\varphi_j = (\varphi_k \implies \varphi_i)$.

1. $Q \to P$: the rule of inference. "modus ponens".
2.

Other rules (possible members of φ):

- $x = y$, $y = z$ then $x = z$.
- If $\varphi_i = \forall x \varphi(x)$, then also $\forall y \varphi(y)$ in the sequence.
- If $\forall x \varphi(x)$ also $\varphi(\tau(\bar{c}))$.

Definition 2.0.5

A set of sentences is a consistent theory if there is no φ such that φ and $\neg\varphi$ are both in the theory. T is inconsistent if it is not consistent.