Logic

Chapter 1

Propositional Logic

1.1 The Language of Propositional Logic

Definition 1.1. Let V be a countably infinite set, whose elements are called **propositional variables**. We define the set of **formulas** as the minimal set of strings on the alphabet $V \cup \{\neg, \rightarrow, (,)\}$ satisfying the following properties.

(a) Each propositional variable in V is a formula on V.

(b) If α is a formula, then so is $\neg\alpha$.

(c) If α and β are formulas, then so is $(\alpha \rightarrow \beta)$.

1.2 Truth Assignment

Definition 1.2. A **truth assignment** is a function $\tau : V \to \{0,1\}$, and it can be extended to have its domain the set of formulas as follows.

(a) $\tau(\neg\alpha) = 1 - \tau(\alpha)$ for any formula α.

(b) $\tau((\alpha \to \beta)) = 1 - \tau(\alpha)(1 - \tau(\beta))$ for any formulas α and β.

Definition 1.3. We say that a truth assignment τ **satisfies** a formula α if $\tau(\alpha) = 1$. Also, we say that τ **satisfies** a set Σ of formulas if it satisfies each formula in Σ.

Definition 1.4. Let Γ be a set of formulas and let α be a formula. We say that Γ **tautologically implies** α, denoted by $\Gamma \vDash \alpha$, if every truth assignment satisfying Γ also satisfies α.

1.3 Proof System

Definition 1.5. The collection Λ of **axioms** consists of the formulas listed below, where α, β, γ are formulas.

(A1) $\alpha \to (\beta \to \alpha)$.

(A2) $(\alpha \to (\beta \to \gamma)) \to ((\alpha \to \beta) \to (\alpha \to \gamma))$.

(A3) $(\neg\beta \to \neg\alpha) \to (\alpha \to \beta)$.

Definition 1.6. A **proof** of a formula α from a collection Γ of formulas is a sequence of formulas

$$(\alpha_1, \alpha_2, \dots, \alpha_n)$$

satisfying the following properties.

(a) $\alpha_n = \alpha$.

(b) For $k \in \{1, 2, \dots, n\}$, either $\alpha_k \in \Lambda \cup \Gamma$ or there exist $i, j \in \{1, 2, \dots, k-1\}$ with $\alpha_j = \alpha_i \to \alpha_k$.

If there exists a proof of φ from Γ, we write $\Gamma \vdash \varphi$. If $\varnothing \vdash \varphi$, we write $\vdash \varphi$ for short.

Theorem 1.7 (Law of Identity). For any formula α, we have $\vdash \alpha \to \alpha$.

Proof. We have a proof of $\alpha \to \alpha$ as follows.

(1) $(\alpha \to ((\alpha \to \alpha) \to \alpha)) \to ((\alpha \to (\alpha \to \alpha)) \to (\alpha \to \alpha))$. (A2)

(2) $\alpha \to ((\alpha \to \alpha) \to \alpha)$. (A1)

(3) $(\alpha \to (\alpha \to \alpha)) \to (\alpha \to \alpha)$. (1, 2)

(4) $\alpha \to (\alpha \to \alpha)$. (A1)

(5) $\alpha \to \alpha$. (3, 4)

Thus, we can conclude that $\vdash \alpha \to \alpha$. $\square$

Theorem 1.8 (Duns Scotus Law). For any formula α and β, we have $\vdash \neg\alpha \to (\alpha \to \beta)$.

Proof. We have a proof of $\neg\alpha \to (\alpha \to \beta)$ as follows.

(1) $((\neg\beta \to \neg\alpha) \to (\alpha \to \beta)) \to (\neg\alpha \to ((\neg\beta \to \neg\alpha) \to (\alpha \to \beta)))$. (A1)

(2) $(\neg\beta \to \neg\alpha) \to (\alpha \to \beta)$. (A3)

(3) $\neg\alpha \to ((\neg\beta \to \neg\alpha) \to (\alpha \to \beta))$. (1, 2)

(4) $(\neg\alpha \to ((\neg\beta \to \neg\alpha) \to (\alpha \to \beta))) \to ((\neg\alpha \to (\neg\beta \to \neg\alpha)) \to (\neg\alpha \to (\alpha \to \beta)))$. (A2)

(5) $(\neg\alpha \to (\neg\beta \to \neg\alpha)) \to (\neg\alpha \to (\alpha \to \beta))$. (3, 4)

(6) $\neg\alpha \to (\neg\beta \to \neg\alpha)$. (A1)

(7) $\neg\alpha \to (\alpha \to \beta)$. (5, 6)

Thus, we can conclude that $\vdash \neg\alpha \to (\alpha \to \beta)$. $\square$

Theorem 1.9 (Modus Ponens). For any formula α and β, we have $\vdash \alpha \to ((\alpha \to \beta) \to \beta)$.

Proof. We have a proof of $\alpha \to ((\alpha \to \beta) \to \beta)$ as follows.

(1) $(\alpha \to \beta) \to (\alpha \to \beta)$. (Theorem 1.7)

(2) $((\alpha \to \beta) \to (\alpha \to \beta)) \to (((\alpha \to \beta) \to \alpha) \to ((\alpha \to \beta) \to \beta))$. (A2)

(3) $((\alpha \to \beta) \to \alpha) \to ((\alpha \to \beta) \to \beta)$. (1, 2)

(4) $(((\alpha \to \beta) \to \alpha) \to ((\alpha \to \beta) \to \beta)) \to (\alpha \to (((\alpha \to \beta) \to \alpha) \to ((\alpha \to \beta) \to \beta)))$. (A1)

(5) $\alpha \to (((\alpha \to \beta) \to \alpha) \to ((\alpha \to \beta) \to \beta))$. (3, 4)

(6) $(\alpha \to (((\alpha \to \beta) \to \alpha) \to ((\alpha \to \beta) \to \beta))) \to ((\alpha \to ((\alpha \to \beta) \to \alpha)) \to (\alpha \to ((\alpha \to \beta) \to \beta)))$. (A2)

(7) $(\alpha \to ((\alpha \to \beta) \to \alpha)) \to (\alpha \to ((\alpha \to \beta) \to \beta))$. (5, 6)

(8) $\alpha \to ((\alpha \to \beta) \to \alpha)$. (A1)

(9) $\alpha \to ((\alpha \to \beta) \to \beta)$. (7, 8)

Thus, we can conclude that $\vdash \alpha \to ((\alpha \to \beta) \to \beta)$. $\square$

Theorem 1.10 (Hypothetical Syllogism). For any formulas α, β and γ, we have $\vdash (\beta \to \gamma) \to ((\alpha \to \beta) \to (\alpha \to \gamma))$.

Proof. We have a proof of $(\beta \to \gamma) \to ((\alpha \to \beta) \to (\alpha \to \gamma))$ as follows.

(1) $(\alpha \to (\beta \to \gamma)) \to ((\alpha \to \beta) \to (\alpha \to \gamma))$. (A2)

(2) $((\alpha \to (\beta \to \gamma)) \to ((\alpha \to \beta) \to (\alpha \to \gamma))) \to ((\beta \to \gamma) \to ((\alpha \to (\beta \to \gamma)) \to ((\alpha \to \beta) \to (\alpha \to \gamma))))$. (A1)

(3) $(\beta \to \gamma) \to ((\alpha \to (\beta \to \gamma)) \to ((\alpha \to \beta) \to (\alpha \to \gamma)))$. (1, 2)

(4) $((\beta \to \gamma) \to ((\alpha \to (\beta \to \gamma)) \to ((\alpha \to \beta) \to (\alpha \to \gamma)))) \to (((\beta \to \gamma) \to (\alpha \to (\beta \to \gamma))) \to ((\beta \to \gamma) \to ((\alpha \to \beta) \to (\alpha \to \gamma))))$. (A2)

(5) $((\beta \to \gamma) \to (\alpha \to (\beta \to \gamma))) \to ((\beta \to \gamma) \to ((\alpha \to \beta) \to (\alpha \to \gamma)))$. (3, 4)

(6) $(\beta \to \gamma) \to (\alpha \to (\beta \to \gamma))$. (A1)

(7) $(\beta \to \gamma) \to ((\alpha \to \beta) \to (\alpha \to \gamma))$. (5, 6)

Thus, we can conclude that $\vdash (\beta \to \gamma) \to ((\alpha \to \beta) \to (\alpha \to \gamma))$. $\square$

Theorem 1.11 (Clavius's Law). For any formula α, we have $\vdash (\neg\alpha \to \alpha) \to \alpha$.

Proof. We have a proof of $(\neg\alpha \to \alpha) \to \alpha$ as follows.

(1) $(\neg\alpha \to (\alpha \to \neg(\neg\alpha \to \alpha))) \to ((\neg\alpha \to \alpha) \to (\neg\alpha \to \neg(\neg\alpha \to \alpha)))$. (A2)

(2) $\neg\alpha \to (\alpha \to \neg(\neg\alpha \to \alpha))$. (Theorem 1.8)

(3) $(\neg\alpha \to \alpha) \to (\neg\alpha \to \neg(\neg\alpha \to \alpha))$. (1, 2)

(4) $(\neg\alpha \to \neg(\neg\alpha \to \alpha)) \to ((\neg\alpha \to \alpha) \to \alpha)$. (A3)

(5) $((\neg\alpha \to \neg(\neg\alpha \to \alpha)) \to ((\neg\alpha \to \alpha) \to \alpha)) \to (((\neg\alpha \to \alpha) \to (\neg\alpha \to \neg(\neg\alpha \to \alpha))) \to ((\neg\alpha \to \alpha) \to ((\neg\alpha \to \alpha) \to \alpha)))$. (Theorem 1.10)

(6) $((\neg\alpha \to \alpha) \to (\neg\alpha \to \neg(\neg\alpha \to \alpha))) \to ((\neg\alpha \to \alpha) \to ((\neg\alpha \to \alpha) \to \alpha))$. (4, 5)

(7) $(\neg\alpha \to \alpha) \to ((\neg\alpha \to \alpha) \to \alpha)$. (3, 6)

(8) $((\neg\alpha \to \alpha) \to ((\neg\alpha \to \alpha) \to \alpha)) \to (((\neg\alpha \to \alpha) \to (\neg\alpha \to \alpha)) \to ((\neg\alpha \to \alpha) \to \alpha))$. (A2)

(9) $((\neg\alpha \to \alpha) \to (\neg\alpha \to \alpha)) \to ((\neg\alpha \to \alpha) \to \alpha)$ (7, 8)

(10) $(\neg\alpha \to \alpha) \to (\neg\alpha \to \alpha)$. (Theorem 1.7)

(11) $(\neg\alpha \to \alpha) \to \alpha$. (9, 10)

Thus, we can conclude that $\vdash (\neg\alpha \to \alpha) \to \alpha$. □

Theorem 1.12 (Elimination of Double Negation). For any formula α, we have $\vdash \neg\neg\alpha \to \alpha$.

Proof. We have a proof of $\neg\neg\alpha \to \alpha$ as follows.

(1) $((\neg\alpha \to \alpha) \to \alpha) \to ((\neg\neg\alpha \to (\neg\alpha \to \alpha)) \to (\neg\neg\alpha \to \alpha))$. (Theorem 1.10)

(2) $(\neg\alpha \to \alpha) \to \alpha$. (Theorem 1.11)

(3) $(\neg\neg\alpha \to (\neg\alpha \to \alpha)) \to (\neg\neg\alpha \to \alpha)$. (1, 2)

(4) $\neg\neg\alpha \to (\neg\alpha \to \alpha)$. (Theorem 1.8)

(5) $\neg\neg\alpha \to \alpha$. (3, 4)

Thus, we can conclude that $\vdash \neg\neg\alpha \to \alpha$. □

Theorem 1.13 (Introduction of Double Negation). For any formula α, we have $\vdash \alpha \to \neg\neg\alpha$.

Proof. We have a proof of $\alpha \to \neg\neg\alpha$ as follows.

(1) $(\neg\neg\neg\alpha \to \neg\alpha) \to (\alpha \to \neg\neg\alpha)$. (A3)

(2) $\neg\neg\neg\alpha \to \neg\alpha$. (Theorem 1.12)

(3) $\alpha \to \neg\neg\alpha$. (1, 2)

Thus, we can conclude that $\vdash \alpha \to \neg\neg\alpha$. □

Theorem 1.14 (Law of Contraposition). For any formulas α and β, we have $\vdash (\alpha \to \beta) \to (\neg\beta \to \neg\alpha)$.

Proof. We have a proof of $(\alpha \to \beta) \to (\neg\beta \to \neg\alpha)$ as follows.

(1) $(\beta \to \neg\neg\beta) \to ((\neg\neg\alpha \to \beta) \to (\neg\neg\alpha \to \neg\neg\beta))$. (Theorem 1.10)

(2) $\beta \to \neg\neg\beta$. (Theorem 1.13)

(3) $(\neg\neg\alpha \to \beta) \to (\neg\neg\alpha \to \neg\neg\beta)$. (1, 2)

(4) $((\neg\neg\alpha \to \beta) \to (\neg\neg\alpha \to \neg\neg\beta)) \to ((\alpha \to \beta) \to ((\neg\neg\alpha \to \beta) \to (\neg\neg\alpha \to \neg\neg\beta)))$. (A1)

(5) $(\alpha \to \beta) \to ((\neg\neg\alpha \to \beta) \to (\neg\neg\alpha \to \neg\neg\beta))$. (3, 4)

(6) $(\alpha \to \beta) \to ((\neg\neg\alpha \to \alpha) \to (\neg\neg\alpha \to \beta))$. (Theorem 1.10)

(7) $((\alpha \to \beta) \to ((\neg\neg\alpha \to \alpha) \to (\neg\neg\alpha \to \beta))) \to (((\alpha \to \beta) \to (\neg\neg\alpha \to \alpha)) \to ((\alpha \to \beta) \to (\neg\neg\alpha \to \beta)))$. (A2)

(8) $((\alpha \to \beta) \to (\neg\neg\alpha \to \alpha)) \to ((\alpha \to \beta) \to (\neg\neg\alpha \to \beta))$. (6, 7)

(9) $(\neg\neg\alpha \to \alpha) \to ((\alpha \to \beta) \to (\neg\neg\alpha \to \alpha))$. (A1)

(10) $\neg\neg\alpha \to \alpha$. (Theorem 1.12)

(11) $(\alpha \to \beta) \to (\neg\neg\alpha \to \alpha)$. (9, 10)

(12) $(\alpha \to \beta) \to (\neg\neg\alpha \to \beta)$. (8, 11)

(13) $((\alpha \to \beta) \to ((\neg\neg\alpha \to \beta) \to (\neg\neg\alpha \to \neg\neg\beta))) \to (((\alpha \to \beta) \to (\neg\neg\alpha \to \beta)) \to ((\alpha \to \beta) \to (\neg\neg\alpha \to \neg\neg\beta)))$. (A2)

(14) $((\alpha \to \beta) \to (\neg\neg\alpha \to \beta)) \to ((\alpha \to \beta) \to (\neg\neg\alpha \to \neg\neg\beta))$. (5, 13)

(15) $(\alpha \to \beta) \to (\neg\neg\alpha \to \neg\neg\beta)$. (12, 14)

(16) $((\neg\neg\alpha \to \neg\neg\beta) \to (\neg\beta \to \neg\alpha)) \to (((\alpha \to \beta) \to (\neg\neg\alpha \to \neg\neg\beta)) \to ((\alpha \to \beta) \to (\neg\beta \to \neg\alpha)))$. (Theorem 1.10)

(17) $(\neg\neg\alpha \to \neg\neg\beta) \to (\neg\beta \to \neg\alpha)$. (A3)

(18) $((\alpha \to \beta) \to (\neg\neg\alpha \to \neg\neg\beta)) \to ((\alpha \to \beta) \to (\neg\beta \to \neg\alpha))$. (16, 17)

(19) $(\alpha \to \beta) \to (\neg\beta \to \neg\alpha)$. (15, 18)

Thus, we can conclude that $\vdash (\alpha \to \beta) \to (\neg\beta \to \neg\alpha)$. □

Theorem 1.15. For any formulas α and β, we have $\vdash \alpha \to (\neg\beta \to \neg(\alpha \to \beta))$.

Proof. We have a proof of $\alpha \to (\neg\beta \to \neg(\alpha \to \beta))$ as follows.

(1) $((\alpha \to \beta) \to \beta) \to (\neg\beta \to \neg(\alpha \to \beta))$. (Theorem 1.14)

(2) $(((\alpha \to \beta) \to \beta) \to (\neg\beta \to \neg(\alpha \to \beta))) \to (\alpha \to (((\alpha \to \beta) \to \beta) \to (\neg\beta \to \neg(\alpha \to \beta))))$. (A1)

(3) $\alpha \to (((\alpha \to \beta) \to \beta) \to (\neg\beta \to \neg(\alpha \to \beta)))$. (1, 2)

(4) $(\alpha \to (((\alpha \to \beta) \to \beta) \to (\neg\beta \to (\neg(\alpha \to \beta))))) \to ((\alpha \to ((\alpha \to \beta) \to \beta)) \to (\alpha \to (\neg\beta \to (\neg(\alpha \to \beta)))))$. (A2)

(5) $(\alpha \to ((\alpha \to \beta) \to \beta)) \to (\alpha \to (\neg\beta \to (\neg(\alpha \to \beta))))$. (3, 4)

(6) $\alpha \to ((\alpha \to \beta) \to \beta)$. (Theorem 1.9)

(7) $\alpha \to (\neg\beta \to \neg(\alpha \to \beta))$. (5, 6)

Thus, we can conclude that $\vdash \alpha \to (\neg\beta \to \neg(\alpha \to \beta))$. □

Theorem 1.16 (Deduction Theorem). Let Γ be a set of formulas and let α and β be formulas. If $\Gamma \cup \{\alpha\} \vdash \beta$, then $\Gamma \vdash \alpha \to \beta$.

Proof. If $\beta \in \Lambda \cup \Gamma$, then we have $\Gamma \vdash \alpha \to \beta_k$ since $\vdash \beta_k \to (\alpha \to \beta_k)$. Furthermore, if $\beta = \alpha$, then we also have $\Gamma \vdash \alpha \to \beta$ since $\vdash \beta \to \beta$ by Theorem 1.7. Thus, one only needs to consider the case that $\beta \notin \Lambda \cup \Gamma \cup \{\alpha\}$.

Suppose that $(\beta_1, \beta_2, \ldots, \beta_n)$ is a proof of β from $\Gamma \cup \{\alpha\}$. For $1 \leq k \leq n$, we prove that $\Gamma \vdash \alpha \to \beta_k$ by induction on k. The induction basis holds for $k = 1$ since $\beta_1 \in \Lambda \cup \Gamma \cup \{\alpha\}$. For the induction step, let $k \geq 2$ and assume that $\Gamma \vdash \alpha \to \beta_\ell$ for $1 \leq \ell < k$. We have proved for the case that $\beta \in \Lambda \cup \Gamma \cup \{\alpha\}$, and thus we assume without loss of generality that there exist $1 \leq i < k$ and $1 \leq j < k$ such that $\beta_j = \beta_i \to \beta_k$. Note that $\Gamma \vdash \alpha \to \beta_i$ and $\Gamma \vdash \alpha \to (\beta_i \to \beta_k)$ hold by induction hypothesis. Therefore, since

$$\vdash (\alpha \to (\beta_i \to \beta_k)) \to ((\alpha \to \beta_i) \to (\alpha \to \beta_k)),$$

we can conclude that $\Gamma \vdash \alpha \to \beta_k$, which completes the proof. □

1.4 Soundness and Completeness

Theorem 1.17. Let α be a formula which consists of only the propositional variables $p_1, \ldots, p_k$ and let τ be a truth assignment. Let $p_1^*, \ldots, p_k^*$ be formulas such that for each $i \in \{1, \ldots, k\}$,

$$p_i^* = \begin{cases} p_i, & \text{if } \tau(p_i) = 1 \\ \neg p_i, & \text{if } \tau(p_i) = 0. \end{cases}$$

Furthermore, let α^* be the formula defined by

$$\alpha^* = \begin{cases} \alpha, & \text{if } \tau(\alpha) = 1 \\ \neg \alpha, & \text{if } \tau(\alpha) = 0. \end{cases}$$

Then we have

$$\{p_1^*, \ldots, p_k^*\} \vdash \alpha^*.$$

Proof. The proof is by induction on the complexity of α. It is straightforward that the theorem holds when $\alpha = p_i$ for some $i \in \{1, \ldots, k\}$.

Now suppose that $\{p_1^*, \ldots, p_k^*\} \vdash \alpha^*$, and we prove that

$$\{p_1^*, \ldots, p_k^*\} \vdash \beta^*$$

with $\beta = \neg\alpha$. If $\tau(\alpha) = 0$, then $\tau(\beta) = 1$, and we have $\alpha^* = \neg\alpha = \beta^*$. Thus, $\{p_1^*, \ldots, p_k^*\} \vdash \beta^*$. If $\tau(\alpha) = 1$, then $\tau(\beta) = 0$, and we have $\alpha^* = \alpha$ and $\beta^* = \neg\neg\alpha$. Since

$$\{p_1^*, \ldots, p_k^*\} \vdash \alpha \quad \text{and} \quad \vdash \alpha \to \neg\neg\alpha,$$

we have $\{p_1^*, \ldots, p_k^*\} \vdash \beta^*$.

Now suppose that $\{p_1^*, \ldots, p_k^*\} \vdash \alpha^*$ and $\{p_1^*, \ldots, p_k^*\} \vdash \beta^*$, and we prove that

$$\{p_1^*, \ldots, p_k^*\} \vdash \gamma^*$$

with $\gamma = \alpha \to \beta$. If $\tau(\alpha) = 0$, then $\tau(\gamma) = 1$, and we have $\alpha^* = \neg\alpha$ and $\gamma^* = \alpha \to \beta$. Since $\{p_1^*, \ldots, p_k^*\} \vdash \neg\alpha$

$$\{p_1^*, \ldots, p_k^*\} \vdash \neg\alpha \quad \text{and} \quad \vdash \neg\alpha \to (\alpha \to \beta)$$

we have $\{p_1^*, \ldots, p_k^*\} \vdash \gamma^*$. If $\tau(\beta) = 1$, then $\tau(\gamma) = 1$, and we have $\beta^* = \beta$ and $\gamma^* = \alpha \to \beta$. Since

$$\{p_1^*, \ldots, p_k^*\} \vdash \beta \quad \text{and} \quad \vdash \beta \to (\alpha \to \beta)$$

we have $\{p_1^*, \ldots, p_k^*\} \vdash \gamma^*$. If $\tau(\alpha) = 1$ and $\tau(\beta) = 0$, then $\tau(\gamma) = 0$, and we have $\alpha^* = \alpha$, $\beta^* = \neg\beta$ and $\gamma^* = \neg(\alpha \to \beta)$. Since

$$\{p_1^*, \ldots, p_k^*\} \vdash \alpha, \quad \{p_1^*, \ldots, p_k^*\} \vdash \neg\beta, \quad \text{and} \quad \vdash \alpha \to (\neg\beta \to \neg(\alpha \to \beta)),$$

we have $\{p_1^*, \ldots, p_k^*\} \vdash \gamma^*$, completing the proof. □

Chapter 2

First-Order Logic

2.1 The Language of First-Order Logic

Definition 2.1. A **language** L is a disjoint union of a set L_{rel} of **relation symbols** and a set L_{fun} of **function symbols**, where each symbol has an arity.

Definition 2.2. Let L be a language. Let V be a countably infinite set, whose elements are called **variables**. A **term** is a string obtained as follows.

(a) Each variable is a term.

(b) If f is an n-ary function symbol and $t_1, \ldots, t_n$ are terms, then $f(t_1, \ldots, t_n)$ is a term.

A **formula** is a string obtained as follows.

(a) If R is an n-ary relation symbol and $t_1, \ldots, t_n$ are terms, then $R(t_1, \ldots, t_n)$ is a formula.

(b) If α is a formula, then so is $\neg\alpha$.

(c) If α and β are formulas, then so is $(\alpha \to \beta)$.

(d) If α is a formula and x is a variable, then $\forall x \alpha$ is a formula.

2.2 Structures

Definition 2.3. Let L be a language. A **structure** for L is a triple

$$M = \left(U, (R^M)_{R \in L_{\mathrm{rel}}}, (f^M)_{f \in L_{\mathrm{fun}}}\right),$$

where each component is as follows.

- U is a nonempty set called **universe**.
- To each n-ary relation symbol R an n-ary relation $R^M \subseteq U^n$ is assigned.
- To each n-ary function symbol f an n-ary function $f^M : U^n \to U$ is assigned.

Definition 2.4. Let L be a language and let M is a structure for L. An **object assignment** is a function $\sigma : V \to U$, and it can be extended to have its domain the set of terms such that for any n-ary function symbol f and any terms $t_1, \ldots, t_n$, we have

$$\sigma(f(t_1, \ldots, t_n)) = f^M(\sigma(t_1), \sigma(t_2), \ldots, \sigma(t_n)).$$