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Non-Equivalence of Some Implicational Deduction Theorems

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The paper is substantially based on the forthcoming paper by Petr Cintula (principal author) and the author.

Abstract

We show that some classes of logics in the hierarchy of Implicational Deduction Theorems, defined in the forthcoming paper [1], are not equal. This completes the picture of hierarchy of these logics.

collapses on some level. In this paper we show in full details that some of its members are not the same.

This is shown by presenting, for the remaining case, a counter-example. It is worth to note that this counter-example was found with the help of computer. For further details, proofs and references we refer the reader to the forthcoming paper [1] mentioned already.

1. Introduction

One of the most important theorems of classical propositional logic is the Deduction Theorem, independently discovered by Herbrand [2] and Tarski [3], which connects provability and implication. In its most popular form it says

$$\Gamma, \varphi \vdash \psi \text{ iff } \Gamma \vdash \varphi \rightarrow \psi.$$

It enables us to find some proofs much easier. However, this theorem does not hold in all logics. For example in logics without contraction, we usually have so called Local Deduction Theorem, which says that there exists some natural k such that

$$\Gamma, \varphi \vdash \psi \text{ iff } \Gamma \vdash \underbrace{\varphi \rightarrow (\dots (\varphi \rightarrow \psi) \dots)}_{k\text{-times}}.$$

The problem is that generally we do not have any (reasonable) upper bound on k .

We can try to estimate k somehow. The immediate idea is to count how many times the assumption φ is used in the proof of ψ . This idea is captured in the forthcoming paper [1] where the situation is shown not to be so easy. Authors define some hierarchy of logics with Implicational Deduction Theorems and investigate relations between its members. It is shown that this hierarchy

2. Preliminaries

We use some standard terminology from the theory of logical calculi (see e.g. [4])—a *propositional language* \mathcal{L} (a set of logical connectives with some finite arity, in this paper we have just one binary connective called implication \rightarrow and we use the following convention: $\varphi \rightarrow^0 \psi = \psi$ and $\varphi \rightarrow^{i+1} \psi = \varphi \rightarrow (\varphi \rightarrow^i \psi)$), the set of \mathcal{L} -formulae $Fle_{\mathcal{L}}$ over some fixed countably infinite set of propositional variables and \mathcal{L} -substitutions. An \mathcal{L} -theory Γ is a set of \mathcal{L} -formulae. An \mathcal{L} -consecution $\Gamma \triangleright \varphi$ is a pair consisting of a theory Γ and a formula φ .

A *logic* \mathbf{L} in the language \mathcal{L} is a structural consequence relation (in the sense of Tarski) on $Fle_{\mathcal{L}}$. That is, \mathbf{L} is a set of relations between theories and formulae (writing $\Gamma \vdash_{\mathbf{L}} \varphi$, and $\Gamma \vdash_{\mathbf{L}} \Gamma'$ as an abbreviation for $\Gamma \vdash_{\mathbf{L}} \varphi$ for each $\varphi \in \Gamma'$) satisfying the following conditions:

- (i) If $\varphi \in \Gamma$, then $\Gamma \vdash_{\mathbf{L}} \varphi$.
- (ii) If $\Gamma \vdash_{\mathbf{L}} \Gamma'$ and $\Gamma' \vdash_{\mathbf{L}} \varphi$, then $\Gamma \vdash_{\mathbf{L}} \varphi$.
- (iii) If $\Gamma \vdash_{\mathbf{L}} \varphi$, then there is a finite set $\Gamma' \subseteq \Gamma$ s.t. $\Gamma' \vdash_{\mathbf{L}} \varphi$.
- (iv) If $\Gamma \vdash_{\mathbf{L}} \varphi$, then $\sigma(\Gamma) \vdash_{\mathbf{L}} \sigma(\varphi)$ for any \mathcal{L} -substitution σ .

The previous conditions are called reflexivity, cut, finitariness and structurality.

Definition 1 An axiomatic system \mathcal{AX} is a set of finitary consecutions closed under substitutions. The members of \mathcal{AX} with non-empty theories are called deductive rules, these with empty theories are called axioms. We say that \mathcal{AX} is MP-based if modus ponens is its only deduction rule.

Note that we have only finitary rules, and axioms as well as rules are presented by schemata.

Definition 2 Let \mathcal{AX} be an axiomatic system. An \mathcal{AX} -proof of the formula φ in theory Γ is a finite tree labelled by formulae satisfying

- (i) the root is labelled by φ ,
- (ii) leaves by either axioms or elements of Γ ,
- (iii) if a node is labelled by ψ and its preceding nodes are labelled by ψ_1, \dots, ψ_n then $\{\psi_1, \dots, \psi_n\} \triangleright \varphi \in \mathcal{AX}$.

If such a proof exists we write $\Gamma \vdash_{\mathcal{AX}}^p \varphi$.

We say that \mathcal{AX} is an axiomatic system for (a presentation of) a logic \mathbf{L} iff $\mathbf{L} \vdash_{\mathcal{AX}}^p \varphi$. A logic \mathbf{L} is MP-based if it has some MP-based presentation.

2.1. Matrix models and semantics

A matrix \mathbf{M} for \mathcal{L} is a pair $\langle A, D \rangle$, where A is an \mathcal{L} -algebra and $D \subseteq A$ is the set of designated elements of \mathbf{M} . An \mathbf{M} -evaluation for matrix $\mathbf{M} = \langle A, D \rangle$ is a mapping $e : Fle_{\mathcal{L}} \rightarrow A$ which commutes with all connectives in \mathcal{L} .

Logics can be defined semantically through logical matrices. Any class of \mathcal{L} -matrices \mathcal{C} is called *matrix semantics* for \mathcal{L} . We say $\Gamma \models_{\mathcal{C}} \varphi$ iff for each $\mathbf{M} \in \mathcal{C}$, $\mathbf{M} = \langle A, D \rangle$, and each evaluation e in \mathbf{M} , $e(\varphi) \in D$ whenever $e[\Gamma] \subseteq D$.

Notice that $\models_{\mathcal{C}}$ is a logic for \mathcal{C} being a finite set of finite \mathcal{L} -matrices. By relaxing either of the finiteness conditions we obtain a consequence relation, but not necessarily a finitary one.

3. Implicational Deduction Theorems

In this section we define some basic notions concerning the study of Implicational Deduction Theorems. First, we define an analog to a Local Deduction Theorem.

Definition 3 A logic \mathbf{L} has Simple Implicational Deduction Theorem (IDT_0) if for each theory Γ and formulae φ, ψ :

$$\Gamma, \varphi \vdash_{\mathbf{L}} \psi \text{ iff there is } n \text{ such that } \Gamma \vdash_{\mathbf{L}} \varphi \rightarrow^n \psi.$$

We immediately obtain the following important property of logics with IDT_0 , which is a consequence of our assumptions concerning finitariness.

Lemma 1 A logic \mathbf{L} with IDT_0 is MP-based.

Now we present a finer analysis of Local Deduction Theorems arising from the idea of counting number of occurrences of φ in the leaves of some proof of ψ in Γ and φ .

Definition 4 Let $n > 0$. A logic \mathbf{L} has n -Implicational Deduction Theorem (IDT_n) if

- (i) \mathbf{L} has an MP-based presentation \mathcal{AX} ,
- (ii) for each theory Γ , formula ψ , mutually different formulae φ_i , $1 \leq i \leq n$, and for each \mathcal{AX} -proof \mathcal{P} of ψ in $\Gamma \cup \{\varphi_i \mid 1 \leq i \leq n\}$:

$$\Gamma \vdash \varphi_1 \rightarrow^{j_1} (\varphi_2 \rightarrow^{j_2} \dots (\varphi_n \rightarrow^{j_n} \psi) \dots),$$

where j_i is the number of occurrences of φ_i in the leaves of \mathcal{P} .

It may seem that eg. IDT_2 can be obtained just by double application of IDT_1 , but it is not true.

Example 1 Let us assume that

$$\varphi, \psi, \varphi \rightarrow (\psi \rightarrow \chi) \vdash \chi. \quad (1)$$

IDT_2 gives

$$\varphi \rightarrow (\psi \rightarrow \chi) \vdash \psi \rightarrow (\varphi \rightarrow \chi) \quad (2)$$

and IDT_1 gives

$$\psi, \varphi \rightarrow (\psi \rightarrow \chi) \vdash \varphi \rightarrow \chi, \quad (3)$$

but now we cannot use IDT_1 once again to obtain (2). We only know that $\varphi \rightarrow \chi$ is provable from ψ and $\varphi \rightarrow (\psi \rightarrow \chi)$, but we do not know how many times ψ has to be used.

From now on, we shall use IDT_n also for the class of all logics satisfying IDT_n . The meaning will be obvious from context.

In the paper [1] we prove

Theorem 1

- (i) If a logic \mathbf{L} has IDT_n then \mathbf{L} has IDT_m for any $m \leq n$.
- (ii) If a logic \mathbf{L} has IDT_3 then \mathbf{L} has IDT_m for any $m \geq 3$.
- (iii) $IDT_0 \neq IDT_1$ and $IDT_1 \neq IDT_2$.

The previous theorem shows that the hierarchy of logics with Implicational Deduction Theorems has the following properties

$$IDT_0 \subsetneq IDT_1 \subsetneq IDT_2 \supseteq IDT_3 = IDT_4 = \dots$$

The remaining problem is whether $IDT_2 = IDT_3$ or not, which is the result of this paper. We solve this problem negatively in the next section. Before we proceed we recall an important characterisation lemma:

Lemma 2 Let \mathbf{L} be a logic and $n > 0$ then \mathbf{L} has IDT_n iff

- (i) \mathbf{L} is MP-based,
- (ii) $\vdash_{\mathbf{L}} \varphi \rightarrow \varphi$,
- (iii) for each natural a_i, b_i , for $1 \leq i \leq n$, holds

$$\begin{aligned} & \varphi_1 \rightarrow^{a_1} (\dots (\varphi_n \rightarrow^{a_n} (\chi \rightarrow \psi)) \dots), \\ & \varphi_1 \rightarrow^{b_1} (\dots (\varphi_n \rightarrow^{b_n} \chi) \dots) \\ & \vdash_{\mathbf{L}} \varphi \rightarrow^{a_1+b_1} \dots (\varphi_n \rightarrow^{a_n+b_n} \psi) \dots. \end{aligned}$$

4. $IDT_2 \neq IDT_3$

In this section we prove that there is a logic with IDT_2 but without IDT_3 . The proof is based on the matrix \mathbf{M} in Table 1. The only denoted element of \mathbf{M} is $\mathbf{1}$. Let us note that the matrix was found with the help of computer.

\rightarrow	1	a	b	c	d	e	f	g
1	1	a	b	c	d	e	f	g
a	1	1	a	a	a	c	d	f
b	1	1	1	a	a	b	d	e
c	1	1	1	1	a	a	c	e
d	1	1	1	1	1	a	a	d
e	1	1	1	1	1	1	a	b
f	1	1	1	1	1	1	1	a
g	1	1	1	1	1	1	1	1

Table 1: Model \mathbf{M} .

From now on, we use the following notation. We abbreviate $e(\varphi) =_{\mathbf{M}} \mathbf{1}$ by $\varphi = \mathbf{1}$, because model \mathbf{M} is fixed and the evaluation is obvious from the context. We shall also abbreviate it simply saying φ is $\mathbf{1}$.

Lemma 3 The logic \mathbf{L} given by model \mathbf{M} does not have IDT_3 .

Proof: There is a proof of

$$\varphi, \psi, \varphi \rightarrow (\psi \rightarrow \chi) \vdash \chi,$$

where φ, ψ and $\varphi \rightarrow (\psi \rightarrow \chi)$ are used only once. IDT_3 would give

$$\vdash (\varphi \rightarrow (\psi \rightarrow \chi)) \rightarrow (\psi \rightarrow (\varphi \rightarrow \chi)),$$

which is not true. Consider an evaluation $e(\varphi) = \mathbf{a}, e(\psi) = \mathbf{b}$ and $e(\chi) = \mathbf{g}$. ■

Now we shall show that \mathbf{L} has IDT_2 . First, we establish some useful properties of \mathbf{M} .

Observation 1 The following statements are true in \mathbf{M} :

- (i) $\varphi \rightarrow \varphi = \mathbf{1}$,
- (ii) $\mathbf{1} \rightarrow \varphi = \varphi$,
- (iii) if $\varphi = \mathbf{1}$ and $\varphi \rightarrow \psi = \mathbf{1}$ then $\psi = \mathbf{1}$ (MP holds in \mathbf{M}).

Definition 5 We define the ordering $<$ on the elements of \mathbf{M} by

$$\mathbf{g} < \mathbf{f} < \mathbf{e} < \mathbf{d} < \mathbf{c} < \mathbf{b} < \mathbf{a} < \mathbf{1}.$$

We use $x \leq y$ with the standard meaning $x = y$ or $x < y$. In the very same way as for $=$ we use $\varphi \leq \psi$ which means that for given evaluation e it holds that $e(\varphi) \leq e(\psi)$.

Lemma 4 The model \mathbf{M} has the following properties:

- (i) $\psi \leq \varphi \rightarrow \psi$,
- (ii) $\varphi_0 \leq \varphi$ implies $\varphi \rightarrow \psi \leq \varphi_0 \rightarrow \psi$,
- (iii) $\psi_0 \leq \psi$ implies $\varphi \rightarrow \psi_0 \leq \varphi \rightarrow \psi$.

These properties of implication in \mathbf{M} play a very important role in the rest of the section.

Lemma 5 For any evaluation such that $\varphi_1, \varphi_2, \varphi_3, \varphi_4$ are different from $\mathbf{1}$ holds

$$\varphi_1 \rightarrow (\varphi_2 \rightarrow (\varphi_3 \rightarrow (\varphi_4 \rightarrow \psi))) = \mathbf{1}.$$

Proof: By Lemma 4 the worst case is $\varphi_1 = \varphi_2 = \varphi_3 = \varphi_4 = \mathbf{a}$ and $\psi = \mathbf{g}$, but even for such evaluation lemma holds. ■

Observation 1 and Lemma 5 are very important. From Lemma 2 we immediately obtain that we only need to check finitely many cases to show that logic \mathbf{L} given by model \mathbf{M} has IDT_2 .

Corollary 1 *The logic \mathbf{L} given by model \mathbf{M} has IDT_2 iff*

$$\varphi_1 \rightarrow^{a_1} (\varphi_2 \rightarrow^{a_2} (\chi \rightarrow \psi)) = \mathbf{1} \quad (4)$$

and

$$\varphi_1 \rightarrow^{b_1} (\varphi_2 \rightarrow^{b_2} \chi) = \mathbf{1} \quad (5)$$

imply

$$\varphi_1 \rightarrow^{a_1+b_1} (\varphi_2 \rightarrow^{a_2+b_2} \psi) = \mathbf{1} \quad (6)$$

for any $a_1 + a_2 + b_1 + b_2 < 4$.

Now we can proceed by exhaustive checking of all possible variants, or we can simplify our work significantly as shown by following three lemmata.

Lemma 6 *Given (4) and (5), and if*

- (i) $\psi = \mathbf{1}$,
- (ii) $\chi = \mathbf{1}$,
- (iii) $\chi = \mathbf{g}$,
- (iv) $\varphi_1 = \mathbf{g}$ (for $a_1 + b_1 > 0$),
- (v) $\varphi_2 = \mathbf{g}$ (for $a_1 + b_1 > 0$),

then the condition (6) holds.

Proof: Cases (i), (iv) and (v) are evident. If $\chi = \mathbf{1}$ then

$$\begin{aligned} \mathbf{1} &= \varphi_1 \rightarrow^{a_1} (\varphi_2 \rightarrow^{a_2} (\mathbf{1} \rightarrow \psi)) \\ &= \varphi_1 \rightarrow^{a_1} (\varphi_2 \rightarrow^{a_2} \psi) \\ &\leq \varphi_1 \rightarrow^{a_1+b_1} (\varphi_2 \rightarrow^{a_2+b_2} \psi). \end{aligned}$$

If $\chi = \mathbf{g}$ then $\chi \leq \psi$ and hence

$$\begin{aligned} \mathbf{1} &= \varphi_1 \rightarrow^{b_1} (\varphi_2 \rightarrow^{b_2} \chi) \\ &\leq \varphi_1 \rightarrow^{b_1} (\varphi_2 \rightarrow^{b_2} \psi) \\ &\leq \varphi_1 \rightarrow^{a_1+b_1} (\varphi_2 \rightarrow^{a_2+b_2} \psi). \end{aligned}$$

■

Lemma 7 *Given (4) and (5), and if*

- (i) $a_1 + a_2 = 0$,
- (ii) $b_1 + b_2 = 0$,

then the condition (6) holds.

Proof: Case (i) gives $\chi \rightarrow \psi = \mathbf{1}$ hence $\chi \leq \psi$ and then (5) implies (6). Case (ii) is even easier, because $\chi = \mathbf{1}$ and then (4) implies (6). ■

Lemma 8 *Given (4) and (5), and if*

- (i) $a_1 = 1, a_2 = 0, b_1 = 1, b_2 = 0$,
- (ii) $a_1 = 1, a_2 = 0, b_1 = 0, b_2 = 1$,
- (iii) $a_1 = 0, a_2 = 1, b_1 = 0, b_2 = 1$,
- (iv) $a_1 = 2, a_2 = 0, b_1 = 1, b_2 = 0$,
- (v) $a_1 = 2, a_2 = 0, b_1 = 0, b_2 = 1$,
- (vi) $a_1 = 0, a_2 = 2, b_1 = 0, b_2 = 1$,
- (vii) $a_1 = 1, a_2 = 1, b_1 = 0, b_2 = 1$,

then the condition (6) holds.

Proof: Let us show case (i). Other cases are more or less similar. We have

$$\varphi_1 \rightarrow (\chi \rightarrow \psi) = \mathbf{1}, \quad (7)$$

$$\varphi_1 \rightarrow \chi = \mathbf{1}. \quad (8)$$

Now we have $\varphi_1 \leq \chi$ from (8) and hence $\chi \rightarrow \psi \leq \varphi_1 \rightarrow \psi$. From (7) we have $\varphi_1 \leq \chi \rightarrow \psi$. So we have $\varphi_1 \leq \varphi_1 \rightarrow \psi$. ■

We can now assume that $\varphi_1 \neq \mathbf{1}$ and $\varphi_2 \neq \mathbf{1}$, because $\mathbf{1} \rightarrow \varphi = \varphi$ and consequently $\varphi_1 = \mathbf{1}$ and $\varphi_2 = \mathbf{1}$ is the same as $a_1 = b_1 = 0$ and $a_2 = b_2 = 0$, respectively. In such case all the following instances lead to the cases solved already.

The remaining cases have to be checked separately and in more details. We analyse all possible evaluations and show that (4) and (5) imply (6).

Lemma 9 *Given (4) and (5), and if $a_1 = 0, a_2 = 1, b_1 = 1, b_2 = 0$, then the condition (6) holds.*

Proof: We need to show that

$$\varphi_2 \rightarrow (\chi \rightarrow \psi) = \mathbf{1}, \quad (9)$$

$$\varphi_1 \rightarrow \chi = \mathbf{1} \quad (10)$$

imply

$$\varphi_1 \rightarrow (\varphi_2 \rightarrow \psi) = \mathbf{1}. \quad (11)$$

We prove it by cases. First, if $\psi = \mathbf{a}, \dots, \mathbf{d}$ then it is easy to show that $\varphi_1 \rightarrow (\varphi_2 \rightarrow \psi) = \mathbf{1}$ (we assume $\varphi_1 \neq \mathbf{1}$ and $\varphi_2 \neq \mathbf{1}$). The only interesting cases are the following:

$\cdot \psi = \mathbf{e}$

$\cdot \varphi_2 = \mathbf{a}$

$\cdot \varphi_1 = \mathbf{a}, \mathbf{b}$ then $\varphi_1 \leq \chi$ from (10), hence $\chi \geq \mathbf{b}$ and therefore $\varphi_2 \rightarrow (\chi \rightarrow \psi) < \mathbf{1}$.

$\cdot \varphi_1 = \mathbf{c}, \dots$ then $\varphi_1 \rightarrow (\varphi_2 \rightarrow \psi) = \mathbf{1}$.

$\cdot \varphi_2 = \mathbf{b}$

$\cdot \varphi_1 = \mathbf{a}$ then $\chi \geq \mathbf{a}$ and therefore $\varphi_2 \rightarrow (\chi \rightarrow \psi) < \mathbf{1}$.

$\cdot \varphi_1 = \mathbf{b}, \dots$ then $\varphi_1 \rightarrow (\varphi_2 \rightarrow \psi) = \mathbf{1}$.

$\cdot \varphi_2 = \mathbf{c}, \dots$ then $\varphi_1 \rightarrow (\varphi_2 \rightarrow \psi) = \mathbf{1}$.

$\cdot \psi = \mathbf{f}$

$\cdot \varphi_2 = \mathbf{a}, \mathbf{b}$

$\cdot \varphi_1 = \mathbf{a}, \mathbf{b}, \mathbf{c}$ then $\chi \geq \mathbf{c}$ and therefore $\varphi_2 \rightarrow (\chi \rightarrow \psi) < \mathbf{1}$.

$\cdot \varphi_1 = \mathbf{d}, \dots$ then $\varphi_1 \rightarrow (\varphi_2 \rightarrow \psi) = \mathbf{1}$.

$\cdot \varphi_2 = \mathbf{c}$

$\cdot \varphi_1 = \mathbf{a}, \mathbf{b}$ $\chi \geq \mathbf{b}$ then $\varphi_2 \rightarrow (\chi \rightarrow \psi) < \mathbf{1}$.

$\cdot \varphi_1 = \mathbf{c}, \dots$ then $\varphi_1 \rightarrow (\varphi_2 \rightarrow \psi) = \mathbf{1}$.

$\cdot \varphi_2 = \mathbf{d}, \dots$ then $\varphi_1 \rightarrow (\varphi_2 \rightarrow \psi) = \mathbf{1}$.

$\cdot \psi = \mathbf{g}$

$\cdot \varphi_2 = \mathbf{a}$

$\cdot \varphi_1 = \mathbf{a}, \dots, \mathbf{e}$ then $\chi \geq \mathbf{e}$ and therefore $\varphi_2 \rightarrow (\chi \rightarrow \psi) < \mathbf{1}$.

$\cdot \varphi_1 = \mathbf{f}, \dots$ then $\varphi_1 \rightarrow (\varphi_2 \rightarrow \psi) = \mathbf{1}$.

$\cdot \varphi_2 = \mathbf{b}, \mathbf{c}$

$\cdot \varphi_1 = \mathbf{a}, \dots, \mathbf{d}$ then $\chi \geq \mathbf{d}$ and therefore $\varphi_2 \rightarrow (\chi \rightarrow \psi) < \mathbf{1}$.

$\cdot \varphi_1 = \mathbf{e}, \dots$ then $\varphi_1 \rightarrow (\varphi_2 \rightarrow \psi) = \mathbf{1}$.

$\cdot \varphi_2 = \mathbf{d}$

$\cdot \varphi_1 = \mathbf{a}, \mathbf{b}, \mathbf{c}$ then $\chi \geq \mathbf{c}$ and therefore $\varphi_2 \rightarrow (\chi \rightarrow \psi) < \mathbf{1}$.

$\cdot \varphi_1 = \mathbf{d}, \dots$ then $\varphi_1 \rightarrow (\varphi_2 \rightarrow \psi) = \mathbf{1}$.

$\cdot \varphi_2 = \mathbf{e}$

$\cdot \varphi_1 = \mathbf{a}$ then $\chi \geq \mathbf{a}$ and therefore $\varphi_2 \rightarrow (\chi \rightarrow \psi) < \mathbf{1}$.

$\cdot \varphi_1 = \mathbf{b}, \dots$ then $\varphi_1 \rightarrow (\varphi_2 \rightarrow \psi) = \mathbf{1}$.

$\cdot \varphi_2 = \mathbf{f}, \dots$ then $\varphi_1 \rightarrow (\varphi_2 \rightarrow \psi) = \mathbf{1}$.

So if $a_1 + a_2 + b_1 + b_2 = 3$ then we need to check only $\psi = \mathbf{g}$ case.

Lemma 10 *Given (4) and (5), and if $a_1 = 0$, $a_2 = 2$, $b_1 = 1$, $b_2 = 0$, then the condition (6) holds.*

Proof: We need to show that

$$\varphi_2 \rightarrow (\varphi_2 \rightarrow (\chi \rightarrow \psi)) = \mathbf{1}, \quad (12)$$

$$\varphi_1 \rightarrow \chi = \mathbf{1} \quad (13)$$

imply

$$\varphi_1 \rightarrow (\varphi_2 \rightarrow (\varphi_2 \rightarrow \psi)) = \mathbf{1}. \quad (14)$$

We prove it by cases:

$\cdot \psi = \mathbf{g}$

$\cdot \varphi_2 = \mathbf{a}$

$\cdot \varphi_1 = \mathbf{a}, \mathbf{b}, \mathbf{c}$ then $\varphi_1 \leq \chi$ from (13), hence $\chi \geq \mathbf{c}$ and therefore (12) does not hold.

$\cdot \varphi_2 = \mathbf{b}$

$\cdot \varphi_1 = \mathbf{a}$ then $\chi \geq \mathbf{a}$ and therefore (12) does not hold.

In all other cases (14) holds. ■

Lemma 11 *Given (4) and (5), and if $a_1 = 1$, $a_2 = 0$, $b_1 = 2$, $b_2 = 0$, then the condition (6) holds.*

Proof: We need to show that

$$\varphi_1 \rightarrow (\chi \rightarrow \psi) = \mathbf{1}, \quad (15)$$

$$\varphi_1 \rightarrow (\varphi_1 \rightarrow \chi) = \mathbf{1} \quad (16)$$

imply

$$\varphi_1 \rightarrow (\varphi_1 \rightarrow (\varphi_1 \rightarrow \psi)) = \mathbf{1}. \quad (17)$$

The only case to show is:

$\cdot \psi = \mathbf{g}$

$\cdot \varphi_1 = \mathbf{a}$ then $\chi \geq \mathbf{d}$ from (16) and therefore (15) does not hold.

In all other cases (17) holds. ■

Corollary 2 *Given (4) and (5), and if $a_1 = 0$, $a_2 = 1$, $b_1 = 0$, $b_2 = 2$, then the condition (6) holds.*

Let us point out that if $\mathbf{f} \leq \psi$ and φ_0, φ_1 and φ_2 are different from $\mathbf{1}$, then

$$\varphi_0 \rightarrow (\varphi_1 \rightarrow (\varphi_2 \rightarrow \psi)) = \mathbf{1}.$$

Lemma 12 *Given (4) and (5), and if $a_1 = 0$, $a_2 = 1$, $b_1 = 2$, $b_2 = 0$, then the condition (6) holds.*

Proof: We need to show that

$$\varphi_2 \rightarrow (\chi \rightarrow \psi) = \mathbf{1}, \quad (18)$$

$$\varphi_1 \rightarrow (\varphi_1 \rightarrow \chi) = \mathbf{1} \quad (19)$$

imply

$$\varphi_1 \rightarrow (\varphi_1 \rightarrow (\varphi_2 \rightarrow \psi)) = \mathbf{1}. \quad (20)$$

We prove it by cases:

$$\cdot \psi = \mathbf{g}$$

$$\cdot \varphi_2 = \mathbf{a}$$

$\cdot \varphi_1 = \mathbf{a}, \mathbf{b}$ by (19) $\chi \geq \mathbf{e}$ and so (18) fails.

$$\cdot \varphi_2 = \mathbf{b}$$

$\cdot \varphi_1 = \mathbf{a}$ by (19) $\chi \geq \mathbf{d}$ and therefore (18) fails.

$$\cdot \varphi_2 = \mathbf{c}$$

$\cdot \varphi_1 = \mathbf{a}$ by (19) $\chi \geq \mathbf{d}$ and therefore (18) fails.

In all other cases (20) holds. ■

Lemma 13 *Given (4) and (5), and if $a_1 = 1$, $a_2 = 0$, $b_1 = 0$, $b_2 = 2$, then the condition (6) holds.*

Proof: We need to show that

$$\varphi_1 \rightarrow (\chi \rightarrow \psi) = \mathbf{1}, \quad (21)$$

$$\varphi_2 \rightarrow (\varphi_2 \rightarrow \chi) = \mathbf{1} \quad (22)$$

imply

$$\varphi_1 \rightarrow (\varphi_2 \rightarrow (\varphi_2 \rightarrow \psi)) = \mathbf{1}. \quad (23)$$

We prove it by cases:

$$\cdot \psi = \mathbf{g}$$

$$\cdot \varphi_2 = \mathbf{a}$$

$\cdot \varphi_1 = \mathbf{a}, \mathbf{b}, \mathbf{c}$ by (22) $\chi \geq \mathbf{d}$ and so (21) fails.

$$\cdot \varphi_2 = \mathbf{b}$$

$\cdot \varphi_1 = \mathbf{a}$ by (22) $\chi \geq \mathbf{e}$ and therefore (21) fails.

In all other cases (23) holds. ■

Lemma 14 *Given (4) and (5), and if $a_1 = 1$, $a_2 = 1$, $b_1 = 1$, $b_2 = 0$, then the condition (6) holds.*

Proof: We need to show that

$$\varphi_1 \rightarrow (\varphi_2 \rightarrow (\chi \rightarrow \psi)) = \mathbf{1}, \quad (24)$$

$$\varphi_1 \rightarrow \chi = \mathbf{1} \quad (25)$$

imply

$$\varphi_1 \rightarrow (\varphi_1 \rightarrow (\varphi_2 \rightarrow \psi)) = \mathbf{1}. \quad (26)$$

We prove it by cases:

$$\cdot \psi = \mathbf{g}$$

$$\cdot \varphi_2 = \mathbf{a}$$

$\cdot \varphi_1 = \mathbf{a}, \mathbf{b}$ by (25) $\chi \geq \mathbf{b}$ and so (24) fails.

$$\cdot \varphi_2 = \mathbf{b}$$

$\cdot \varphi_1 = \mathbf{a}$ by (25) $\chi \geq \mathbf{a}$ and therefore (24) fails.

$$\cdot \varphi_2 = \mathbf{c}$$

$\cdot \varphi_1 = \mathbf{a}$ by (25) $\chi \geq \mathbf{a}$ and therefore (24) fails.

In all other cases (26) holds. ■

Lemma 15 *Given (4) and (5), and if $a_1 = 1$, $a_2 = 0$, $b_1 = 1$, $b_2 = 1$, then the condition (6) holds.*

Proof: We need to show that

$$\varphi_1 \rightarrow (\chi \rightarrow \psi) = \mathbf{1}, \quad (27)$$

$$\varphi_1 \rightarrow (\varphi_2 \rightarrow \chi) = \mathbf{1} \quad (28)$$

imply

$$\varphi_1 \rightarrow (\varphi_1 \rightarrow (\varphi_2 \rightarrow \psi)) = \mathbf{1}. \quad (29)$$

We prove it by cases:

$$\cdot \psi = \mathbf{g}$$

$$\cdot \varphi_2 = \mathbf{a}$$

$\cdot \varphi_1 = \mathbf{a}$ by Lemma 11.

$\cdot \varphi_1 = \mathbf{b}$ by (28) $\chi \geq \mathbf{d}$ and therefore (27) fails.

$$\cdot \varphi_2 = \mathbf{b}$$

$\cdot \varphi_1 = \mathbf{a}$ by (28) $\chi \geq \mathbf{d}$ and therefore (27) fails.

$\cdot \varphi_1 = \mathbf{b}$ by Lemma 11.

$$\cdot \varphi_2 = \mathbf{c}$$

$\cdot \varphi_1 = \mathbf{a}$ by (28) $\chi \geq \mathbf{e}$ and therefore (27) fails.

In all other cases (29) holds. ■

Lemma 16 Given (4) and (5), and if $a_1 = 0$, $a_2 = 1$, $b_1 = 1$, $b_2 = 1$, then the condition (6) holds.

Proof: We need to show that

$$\varphi_2 \rightarrow (\chi \rightarrow \psi) = \mathbf{1}, \quad (30)$$

$$\varphi_1 \rightarrow (\varphi_2 \rightarrow \chi) = \mathbf{1} \quad (31)$$

imply

$$\varphi_1 \rightarrow (\varphi_2 \rightarrow (\varphi_2 \rightarrow \psi)) = \mathbf{1}. \quad (32)$$

We prove it by cases:

$\cdot \psi = \mathbf{g}$

$\cdot \varphi_2 = \mathbf{a}$

$\cdot \varphi_1 = \mathbf{a}, \mathbf{b}, \mathbf{c}$ by (31) $\chi \geq \mathbf{e}$ and so (30) fails.

$\cdot \varphi_2 = \mathbf{b}$

$\cdot \varphi_1 = \mathbf{a}$ by (31) $\chi \geq \mathbf{d}$ and therefore (30) fails.

In all other cases (32) holds. \blacksquare

Theorem 2 There is a logic with IDT_2 but without IDT_3 .

In Tables 2 and 3 we spell all variants needed by Corollary 1 to show that the logic \mathbf{L} given by \mathbf{M} has IDT_2 , which together with Lemma 3 completes the proof of the previous theorem. Consequently, we obtained the complete picture of hierarchy of Implicational Deduction Theorems

$$\text{IDT}_0 \supsetneq \text{IDT}_1 \supsetneq \text{IDT}_2 \supsetneq \text{IDT}_3 = \text{IDT}_4 = \dots$$

a_1	a_2	b_1	b_2	Solution
0	0	0	0	Lemma 7
1	0	0	0	Lemma 7
0	1	0	0	Lemma 7
0	0	1	0	Lemma 7
0	0	0	1	Lemma 7
2	0	0	0	Lemma 7
0	2	0	0	Lemma 7
0	0	2	0	Lemma 7
0	0	0	2	Lemma 7
1	1	0	0	Lemma 7
1	0	1	0	Lemma 8
1	0	0	1	Lemma 8
0	1	1	0	Lemma 9
0	1	0	1	Lemma 8
0	0	1	1	Lemma 7

Table 2: Proof variants for $a_1 + a_2 + b_1 + b_2 < 3$.

a_1	a_2	b_1	b_2	Solution
3	0	0	0	Lemma 7
0	3	0	0	Lemma 7
0	0	3	0	Lemma 7
0	0	0	3	Lemma 7
2	1	0	0	Lemma 7
2	0	1	0	Lemma 8
2	0	0	1	Lemma 8
1	2	0	0	Lemma 7
0	2	1	0	Lemma 10
0	2	0	1	Lemma 8
1	0	2	0	Lemma 11
0	1	2	0	Lemma 12
0	0	2	1	Lemma 7
1	0	0	2	Lemma 13
0	1	0	2	Corollary 2
0	0	1	2	Lemma 7
1	1	1	0	Lemma 14
1	1	0	1	Lemma 8
1	0	1	1	Lemma 15
0	1	1	1	Lemma 16

Table 3: Proof variants for $a_1 + a_2 + b_1 + b_2 = 3$.

5. Summary

We presented a hierarchy of logics satisfying some Implicational Deduction Theorems. We know that any logic with IDT_i has also IDT_j for any $j \leq i$ and for any $0 \leq i \leq 1$ there is a logic with IDT_i but without IDT_{i+1} . Our paper showed that there is also a logic with IDT_2 but without IDT_3 . Moreover, any logic with IDT_i , for $i \geq 3$, has also IDT_j for any $j \geq i$ and hence any j . This completes the picture of our hierarchy.

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