

Some Notes on Proof Theory and Elements of Ordinal Analysis

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1 Provable Recursion in $\mathbf{I}\Delta_0(\text{exp})$

$\mathbf{I}\Delta_0(\text{exp})$ is a theory in first-order logic in the language:

$$\{=, 0, S, P, +, \dot{-}, \cdot, \exp_2\}$$

where S and P are successor and predecessor functions respectively. Further, we will denote $S(x)$ and $P(x)$ as $x + 1$ and $x \dot{-} 1$ respectively. 2^x stands for $\exp_2(x)$.

The non-logical axioms of $\mathbf{I}\Delta_0(\text{exp})$ are the following list:

- $x + 1 \neq 0$
- $0 \dot{-} 1 = 0$
- $x + 0 = x$
- $x \dot{-} 0 = x$
- $x \cdot 0 = 0$
- $2^0 = 1$
- $x + 1 = y + 1 \rightarrow x = y$
- $(x + 1) \dot{-} 1 = x$
- $x + (y + 1) = (x + y) + 1$
- $x \dot{-} (y + 1) = x \dot{-} y \dot{-} 1$
- $x \cdot (y + 1) = x \cdot y + x$
- $2^{x+1} = 2^x + 2^x$

along with the bounded induction scheme:

$$B(0) \wedge \forall x (B(x) \rightarrow B(x + 1)) \rightarrow \forall x B(x)$$

where B is a Δ -formula, that is a formula one of the following forms (with bounded quantifiers only):

- $B \equiv \forall x < t P(x) \equiv \forall x (x < t \rightarrow P(x))$
- $B \equiv \exists x < t P(x) \equiv \exists x (x < t \wedge P(x))$

A Σ_1 -formula is a formula of the form:

$$\exists \vec{x} B(\vec{x})$$

where $B(\vec{x}) \in \Delta_0$.

Lemma 1.1. $\mathbf{I}\Delta_0(\text{exp})$ proves (the universal closures of):

1. $x = 0 \vee x = (x \dot{-} 1) + 1$
2. $x + (y + z) = (x + y) + z$
3. $x \cdot (y \cdot z) = (x \cdot y) \cdot z$
4. $x \cdot (y + z) = x \cdot y + x \cdot z$
5. $x + y = y + x$
6. $x \cdot y = y \cdot x$
7. $x \dot{-} (y + z) = (x \dot{-} y) \dot{-} z$
8. $2^{x+y} = 2^x \cdot 2^y$

Proof.

1. This is self-evident.
2. If $z = 0$, then $x + y = x + y$. If $z = z' + 1$, then, by applying the IH and the relevant axioms:

$$(x + (y + (z' + 1))) = (x + ((y + z') + 1)) = (x + (y + z')) + 1 = ((x + y) + z') + 1 = (x + y) + (z' + 1)$$

3. If $z = 0$, then $x \cdot (y \cdot 0) = (x \cdot y) \cdot 0$. If $z = z' + 1$, then:

$$x \cdot (y \cdot (z' + 1)) = x \cdot (y \cdot z' + y) = x \cdot (y \cdot z') + x \cdot y = (x \cdot y) \cdot z' + x \cdot y = (x \cdot y) \cdot (z' + 1)$$

4. The rest of the cases are shown by induction on z . Consider the exponentiation law. If $y = 0$, then

$$2^{x+0} = 2^x = 0 + 2^x = 2^x \cdot 0 + 2^x = 2^x \cdot (0 + 1) = 2^x \cdot 2^0$$

If $y = y' + 1$, then:

$$2^{x+(y'+1)} = 2^{(x+y')+1} = 2^x \cdot 2^{y'} + 2^x \cdot 2^{y'} = 2^x \cdot 2^{y'+1}$$

□

Lemma 1.2. $\mathbf{I}\Delta_0(\text{exp})$ proves (the universal closures of):

1. $\neg x < 0$
2. $x \leq 0 \leftrightarrow x = 0$
3. $0 \leq x$
4. $x \leq x$

5. $x < x + 1$
6. $x < y + 1 \leftrightarrow x \leq y$
7. $x \leq y \leftrightarrow x < y \vee x = y$
8. $x \leq y \wedge y \leq z \rightarrow x \leq z$
9. $x < y \wedge y < z \rightarrow x < z$
10. $x \leq y \vee y < x$
11. $x < y \rightarrow x + z < y + z$
12. $x < y \rightarrow x \cdot (z + 1) < y \cdot (z + 1)$
13. $x < 2^x$
14. $x < y \rightarrow 2^x < 2^y$

Proof. Straightforward induction. \square

Definition 1.1. A function $f : \mathbb{N}^k \rightarrow \mathbb{N}$ is *provably Σ_1* or *provably recursive* in an arithmetical theory if there is a Σ_1 formula $F(\vec{x}, y)$, a “defining formula” of f , such that:

1. $f(\vec{n}) = m$ iff $\omega \models f(\vec{n}) = m$
2. $T \vdash \exists y F(\vec{x}, y)$
3. $T \vdash F(\vec{x}, y) \wedge F(\vec{x}, y') \rightarrow y = y'$

If a defining formula $F \in \Delta_0$, then a function f is *provably bounded* in T if there is a term $t(\vec{x})$ such that $T \vdash F(\vec{x}, y) \rightarrow y < t(\vec{x})$.

Theorem 1.1. Let f be a provably recursive in T , then we can conservatively extend T by adding a new function symbol f along with the defining axiom $F(\vec{x}, f(\vec{x}))$.

Proof. Let $\mathcal{M} \models T$, \mathcal{M} can be made into a model (\mathcal{M}, f) where we interpret f as the function which is uniquely determined by the second and third conditions of the definitions above. Let φ be a statement not involving f such that φ is true in (\mathcal{M}, f) , so φ is true in \mathcal{M} as well. By compactness T proves φ . \square

Lemma 1.3. Each term defines a provably bounded function of $\mathbf{I}\Delta_0(\text{exp})$.

Proof. Let f be a function defined by some $\mathbf{I}\Delta_0(\text{exp})$ -term t , that is, $f(\vec{x}) = t(\vec{x})$. Take $y = t(\vec{x})$ as the defining formula for f since $\exists y (y = t(\vec{x}))$ is derivable. If $y' = t(\vec{x}) \wedge y = t(\vec{x})$, then $y = y'$ by transitivity. A formula $y = t(\vec{x})$ is bounded and $y = t$ implies $y < t + 1$. Thus f is provably bounded. \square

Lemma 1.4. Define $2_k(x)$ as $2_0(x) = x$ and $2_{n+1}(x) = 2^{2^n(x)}$. Then for every term $t(x_1, \dots, x_n)$ built up from the constants $0, S, P, +, -, \cdot, exp_2$ there exists $k < \omega$ such that:

$$\mathbf{I}\Delta_0(\text{exp}) \vdash t(x_1, \dots, x_n) < 2_k\left(\sum_{k=0}^n x_k\right)$$

Proof. Let t be a term constructed from subterms t_0 and t_1 by using one of the function constants. Assume that inductively $t_0 < 2_{k_0}(s_0)$ and $t_1 < 2_{k_1}(s_1)$ are both provable for some $k_0, k_1 < \omega$, where s_i is the sum of the variables of t_i for $i = 0, 1$.

Let s be the sum of all variables appearing in either t_0 or t_1 and let $k = \max(k_0, k_1)$. Then one can prove $t_0 < 2_k(s)$ and $t_1 < 2_k(s)$. So one needs to show the following:

1. $t_0 + 1 < 2_{k+1}(s)$
2. $t_0 - 1 < 2_k(s)$
3. $t_0 - t_1 < 2_k(s)$
4. $t_0 \cdot t_1 < 2_k(s)$
5. $t_0 + t_1 < 2_k(s)$
6. $2^{t_0} < 2_k(s)$

So $\mathbf{I}\Delta_0(\text{exp}) \vdash t < 2_{k+1}(s)$. □

Lemma 1.5. Let f be a function defined by composition:

$$f(\vec{x}) = g_0(g_1(\vec{x}), \dots, g_m(\vec{x}))$$

where g_0, g_1, \dots, g_m are functions each of which is provably bounded in $\mathbf{I}\Delta_0(\text{exp})$. Then f is provably bounded in $\mathbf{I}\Delta_0(\text{exp})$.

Proof. Each g_i has a defining formula G_i and, by Lemma 1.4, there is a number $k_i < \omega$ such that:

$$\mathbf{I}\Delta_0(\text{exp}) \vdash \exists y < 2_{k_i}(s) G_i(\vec{x}, y)$$

where s is the sum of elements of \vec{x} . And for $i = 0$ one has:

$$\mathbf{I}\Delta_0(\text{exp}) \vdash \exists y < 2_{k_0}(s_0) G_0(y_1, \dots, y_m, y)$$

where s_0 is the sum of y_1, \dots, y_m .

Let $k = \max\{k_i < \omega \mid i < m + 1\}$ and let $F(\vec{x}, y)$ be the bounded formula:

$$\exists y_1 < 2_k(s) \dots \exists y_m < 2_k(s) C(\vec{x}, y_1, \dots, y_m, y)$$

where $C(\vec{x}, y_1, \dots, y_m, y)$ is the conjunction:

$$G_1(\vec{x}, y_1) \wedge \dots \wedge G_m(\vec{x}, y_m) \wedge G_0(y_1, \dots, y_m, y)$$

F is clearly a defining formula for f such that $\mathbf{I}\Delta_0(\text{exp}) \vdash \exists y F(\vec{x}, y)$.
Moreover, each G_i is unique, so $\mathbf{I}\Delta_0(\text{exp})$ also proves:

$$\begin{aligned} & C(\vec{x}, y_1, \dots, y_m, y) \wedge C(\vec{x}, z_1, \dots, z_m, z) \rightarrow \\ & \rightarrow \bigwedge_{j=1}^m y_j = z_j \wedge G_0(y_1, \dots, y_m, y) \wedge G_0(y_1, \dots, y_m, z) \rightarrow \\ & \rightarrow y = z \end{aligned}$$

so we have (by first order logic):

$$\mathbf{I}\Delta_0(\text{exp}) \vdash F(\vec{x}, y) \wedge F(\vec{x}, z) \rightarrow y = z$$

Thus f is provably Σ_1 in $\mathbf{I}\Delta_0(\text{exp})$, so the rest is to find its bounding term.
 $\mathbf{I}\Delta_0(\text{exp})$ proves the following:

$$C(\vec{x}, y_1, \dots, y_m, y) \rightarrow \bigwedge_{j=1}^m y_j < 2_k(s) \wedge y < 2_k(y_1 + \dots + y_m)$$

and

$$\bigwedge_{j=1}^m y_j < 2_k(s) \rightarrow y_1 + \dots + y_m < 2_k(s) \cdot m$$

Put $t(\vec{x}) = 2_k(2_k(s) \cdot m)$, then we obtain

$$\mathbf{I}\Delta_0(\text{exp}) \vdash C(\vec{x}, y_1, \dots, y_m, y) \rightarrow y < t(\vec{x})$$

and so

$$\mathbf{I}\Delta_0(\text{exp}) \vdash F(\vec{x}, y) \rightarrow y < t(\vec{x})$$

□

Lemma 1.6. Suppose f is defined by bounded minimisation

$$f(\vec{n}, m) = \mu_{k < m} (g(\vec{n}, k) = 0)$$

from a function g which is provably bounded in $\mathbf{I}\Delta_0(\text{exp})$. Then f is provably bounded in $\mathbf{I}\Delta_0(\text{exp})$.

Proof. Let G be a defining formula for g . Let $F(\vec{x}, z, y)$ be the bounded formula

$$y \leq z \wedge \forall i < y \neg G(\vec{x}, i, 0) \wedge (y = z \vee G(\vec{x}, y, 0))$$

$\omega \models F(\vec{n}, m, k)$ iff either k is the least number less than m such that $g(\vec{n}, k) = 0$ or there is no such and $k = m$. Thus it means that k is the value of $f(\vec{n}, m)$, so F is a defining formula for f .

Furthermore

$$\mathbf{I}\Delta_0(\text{exp}) \vdash F(\vec{x}, z, y) \rightarrow y < z + 1$$

so $t(\vec{x}, z) = z + 1$ can be taken as a bounding term for f .

We can prove:

$$F(\vec{x}, z, y) \wedge F(\vec{x}, z, y') \wedge y < y' \rightarrow G(\vec{x}, y, 0) \wedge \neg G(\vec{x}, y, 0)$$

and similarly for interchanged y and y' . So we can prove:

$$F(\vec{x}, z, y) \wedge F(\vec{x}, z, y') \rightarrow \neg y < y' \wedge \neg y' < y$$

As far as $y < y' \vee y' < y \vee y = y'$, we have

$$F(\vec{x}, z, y) \wedge F(\vec{x}, z, y') \rightarrow y = y'$$

Now we have to check that $\mathbf{I}\Delta_0(\text{exp}) \vdash \exists y F(\vec{x}, z, y)$. We construct such y by bounded induction on z .

1. $z = 0$.

$F(\vec{x}, 0, 0)$ is provable since $y = 0 \leftrightarrow y \leq 0$ and $\neg i < 0$. So $\mathbf{I}\Delta_0(\text{exp}) \vdash F(\vec{x}, 0, y)$ is provable.

2. Assume $\exists y F(\vec{x}, z, y)$ is provable, let show that that $\exists y F(\vec{x}, z + 1, y)$ is provable.

We can show $y \leq z \rightarrow y + 1 \leq z + 1$ and, via $i < y + 1 \leftrightarrow i < y \vee i = y$,

$$\begin{aligned} \forall i < y \neg G(\vec{x}, i, 0) \wedge ((y = z) \wedge \neg G(\vec{x}, y, 0)) &\rightarrow \forall i < \\ y + 1 \neg G(\vec{x}, i, 0) \wedge y + 1 = z + 1 & \end{aligned}$$

Therefore

$$F(\vec{x}, z, y) \rightarrow F(\vec{x}, z + 1, y + 1) \vee F(\vec{x}, z + 1, y)$$

and thus:

$$\exists y F(\vec{x}, z, y) \rightarrow \exists y F(\vec{x}, z + 1, y)$$

□

Theorem 1.2. Every elementary function is provably bounded in $\mathbf{I}\Delta_0(\text{exp})$.

Proof. As we know from recursion theory, the class of elementary functions can be characterised as those functions which are definable from 0, S , P , \cdot , $+$, exp_2 , $\dot{-}$ and \cdot by composition and minimisation. And then we apply above lemmas. □

1.1 Proof-theoretic Characterisation

For this section we shall be using a Tait-style formalisation of $\mathbf{ID}_0(\text{exp})$. We have the following logical rules:

$$\begin{array}{c} \frac{}{\Gamma, R\vec{t}, \neg R\vec{t}} \mathbf{Ax} \\[10pt] \frac{\Gamma, A_0, A_1}{\Gamma, A_0 \vee A_1} \vee \qquad \frac{\Gamma, A_0 \quad \Gamma, A_1}{\Gamma, A_0 \wedge A_1} \wedge \\[10pt] \frac{\Gamma, A(t)}{\Gamma, \exists x A(x)} \exists \qquad \frac{\Gamma, A}{\Gamma, \forall x A} \forall \end{array}$$

where $R\vec{t}$ is an atomic formula and x is not free in A in the \forall rule. Here Γ stores all non-logical axioms of $\mathbf{ID}_0(\text{exp})$ along with its negations. We also have the bounded induction rule:

$$\frac{\Gamma, B(0) \quad \Gamma, \neg B(n), B(n+1)}{\Gamma, B(t)} \mathbf{BInd}$$

where B is a bounded formula and t is any term.

Of course, the cut rule is admissible:

$$\frac{\Gamma, A \quad \Gamma, \neg A}{\Gamma} \mathbf{cut}$$

Definition 1.2. Let $\exists \vec{z} B(\vec{z})$ be a closed Σ_1 -formula, then it is *true at m* , written as $m \models \exists \vec{z} B(\vec{z})$, if there exist natural numbers m_1, \dots, m_l such that each $m_i < m$ and $B(\vec{m})$ is true in the standard model.

A finite set Γ of closed Σ_1 -formulas is true at m , written as $m \models \Gamma$ if at least one of them is true at m .

If $\Gamma(x_1, \dots, x_k)$ is a finite set of Σ_1 -formulas whose free variables occur amongst x_1, \dots, x_k . Let $f : \mathbb{N}^k \rightarrow \mathbb{N}$, then $f \models \Gamma(x_1, \dots, x_k)$ we have $f(\vec{n}) \models \Gamma(x_1 := n_1, \dots, x_k := n_k)$ for each $\vec{n} = (n_1, \dots, n_k)$.

Fact 1.1. (Persistence)

1. If $m \leq m'$, then $m \models \exists \vec{z} B(\vec{z})$ implies $m' \models \exists \vec{z} B(\vec{z})$.
2. If $\forall \vec{n} \in \mathbb{N}^k$ $f(\vec{n}) \leq f'(\vec{n})$, then $f(\vec{n}) \models \Gamma(x_1 := n_1, \dots, x_k := n_k)$ implies $f'(\vec{n}) \models \Gamma(x_1 := n_1, \dots, x_k := n_k)$.

Lemma 1.7. Let $\Gamma(\vec{x})$ be a finite set of Σ_1 formulas such that

$$\mathbf{ID}_0(\text{exp}) \vdash \bigvee_{\gamma(\vec{x}) \in \Gamma(\vec{x})} \gamma(\vec{x}).$$

Then there is an elementary function f such that $f \models \Gamma(\vec{x})$ and f is strongly increasing on its variables.

Proof. If Γ is provable in $\mathbf{I}\Delta_0(\exp)$, then it is provable in the Tait-style version of $\mathbf{I}\Delta_0(\exp)$, where all cut formulas are Σ_1 .

If Γ is classically derivable from non-logical axioms A_1, \dots, A_s , then there is a cut-free proof in the Tait calculus of $\neg A_1, \Delta, \Gamma$, where $\Delta = \neg A_2, \dots, \neg A_s$. Let us show how to cancel $\neg A_1$ using a Σ_1 -cut.

If A_1 is an induction axiom on some formula B , then we have a cut-free proof of:

$$B(0) \wedge \forall y(\neg B(y) \vee B(y+1)) \wedge \exists x \neg B(x), \Delta, \Gamma$$

Thus we also have cut-free proofs of $B(0), \Delta, \Gamma$, $\neg B(y), B(y+1), \Delta, \Gamma$ and $\exists x \neg B(x), \Delta, \Gamma$. So we have

$$\frac{\frac{\Delta, \Gamma, B(0) \quad \Delta, \Gamma, \neg B(y), B(y+1)}{\Delta, \Gamma, B(x)} \mathbf{BInd} \quad \frac{\Delta, \Gamma, \forall x B(x)}{\Delta, \Gamma, \forall x B(x)} \forall}{\frac{\Delta, \Gamma, \forall x B(x) \quad \exists x \neg B(x), \Delta, \Gamma}{\Delta, \Gamma} \Sigma_1\text{-cut}}$$

We can similarly cancel each of $\neg A_2, \dots, \neg A_s$ and so obtain the proof of Γ with Σ_1 -cuts only.

Now we choose a proof of $\Gamma(\vec{x})$ and proceed by induction on the height of the proof and determine an elementary function f such that $f \models \Gamma$.

1. If $\Gamma(\vec{x})$ is an axiom, then for all \vec{n} $\Gamma(\vec{n})$ contains a true atom. So for any $f \models \Gamma$. Let us choose $f(\vec{n}) = n_1 + \dots + n_k$.
2. If $\Gamma, B_0 \vee B_1$ is derivable, so is Γ, B_0, B_1 . Note that B_0 and B_1 are both bounded. Let $f \models \Gamma, B_0, B_1$, then $f \models \Gamma, B_0 \vee B_1$.
3. Assume $\Gamma, B_0 \wedge B_1$ is derivable, then Γ, B_0 and Γ, B_1 . By the induction hypothesis we have $f_0 \models \Gamma, B_0$ and $f_1 \models \Gamma, B_1$, so, by persistence, we have $\lambda \vec{n}. f_0(\vec{n}) + f_1(\vec{n}) \models \Gamma, B_0 \wedge B_1$.
4. Assume $\Gamma, \forall y B(y)$ is derivable, then $\Gamma, B(y)$ is derivable and y is not free in Γ . Since all the formulas are Σ_1 , $\forall x B(y)$ must be bounded, so $B(y) = \neg(y < t) \vee B'(y)$ for some term t and for some bounded formula B' . By the induction hypothesis, assume $f_0 \models \Gamma, \neg(y < t), B'(y)$ for some increasing elementary function f_0 . Then we have:

$$f_0(\vec{n}, k) \models \Gamma(\vec{n}), \neg(k < t(\vec{n})), B'(\vec{n}, k)$$

Let g be an increasing elementary function bounding t , define

$$f(\vec{n}) = \sum_{k < g(\vec{n})} f(\vec{n}, k)$$

We have either $f(\vec{n}) \models \Gamma(\vec{n})$ or, by persistence, $B'(\vec{n}, k)$ is true for every $k < t(\vec{n})$. So $f \models \Gamma, \forall y B(y)$ and f is elementary.

5. Assume $\Gamma, \exists y A(y, \vec{x})$ is derivable, so $\Gamma, A(t, \vec{x})$ is derivable for some term t . By the IH, there is elementary f_0 such that for all \vec{n} one has

$$f_0(\vec{n}) \models \Gamma(\vec{n}), A(t(\vec{n}), \vec{n})$$

Then either $f_0(\vec{n}) \models \Gamma(\vec{n})$ or else $f_0(\vec{n})$ bounds true witnesses for all existential quantifiers in $A(t(\vec{n}), \vec{n})$. Choose an elementary function g which is bounding for t . Define $f(\vec{n}) = f_0(\vec{n}) + g(\vec{n})$, then for all \vec{n} either $f(\vec{n}) \models \Gamma(\vec{n})$ or $f(\vec{n}) \models \exists y A(y, \vec{n})$.

6. TODO
7. TODO

□

2 Primitive Recursion and $\mathbf{I}\Sigma_1$

$\mathbf{I}\Sigma_1$ is an arithmetical theory where the induction scheme is restricted to Σ_1 formulas.

Lemma 2.1. Every primitive recursion is provably recursive in $\mathbf{I}\Sigma_1$.

Proof. We have to show represent each primitive recursive function f with a Σ_1 formula $F(\vec{x}, y) := \exists z C(\vec{x}, y, z)$ such that:

1. $f(\vec{n}) = m$ iff $\omega \models F(\vec{x}, y)$.
2. $\mathbf{I}\Sigma_1 \vdash \exists y F(\vec{x}, y)$.
3. $\mathbf{I}\Sigma_1 \vdash F(\vec{x}, y) \wedge F(\vec{x}, y') \rightarrow y = y'$.

□

3 ϵ_0 and Peano Arithmetic

4 \mathbf{RCA}_0

5 \mathbf{WKL}_0

6 \mathbf{ACA}_0

7 \mathbf{ATR}

8 Π_1^1 -comprehension