Reflection principles in weak and strong arithmetics

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Strong fragments of arithmetic

EA = basic theory of Kalmár elementary functions
$\sim I\Delta_0 + EXP$

$I\Sigma_i = EA +$ induction schema

$$\varphi(0) \wedge \forall x\,(\varphi(x) \to \varphi(x+1)) \to \forall x\,\varphi(x) \qquad (\varphi\text{-}IND)$$

for $\varphi \in \Sigma_i$: $\quad \exists x_1\, \forall x_2\, \dots\, Qx_i\, \underbrace{\theta(x_1, \dots, x_i, \dots)}_{\text{bounded quantifiers}}$

Strict hierarchy: $EA \subsetneq I\Sigma_1 \subsetneq I\Sigma_2 \subsetneq \cdots \subsetneq PA$

non-conservative even for universal sentences

General reference: [Bek05]

Weak fragments of arithmetic

PV_1 = basic theory of polynomial-time functions

$T^i_2 = PV_1 + \Sigma^b_i\text{-}IND$

$S^i_2 = PV_1$ + polynomial induction schema

$$\varphi(0) \land \forall x\, (\varphi(\lfloor x/2 \rfloor) \to \varphi(x)) \to \forall x\, \varphi(x) \qquad (\varphi\text{-}PIND)$$

for $\varphi \in \Sigma^b_i$: $\exists x_1 \le t_1\, \forall x_2 \le t_2 \,\dots\, Q x_i \le t_i\, \underbrace{\theta(x_1, \dots, x_i, \dots)}_{\substack{\text{sharply bounded quantifiers} \\ \exists u \le |t|,\ \forall u \le |t|}}$

Hierarchy? $PV_1 \subseteq S^1_2 \subseteq T^1_2 \subseteq S^2_2 \subseteq \cdots \subseteq T_2 = I\Delta_0 + \Omega_1$

$S^i_2 \subseteq T^i_2$: conjectured non-conservative for universal sentences

$T^i_2 \subseteq S^{i+1}_2$: $\forall\Sigma^b_{i+1}$-conservative, still conjectured strict

General reference: [Kra95], [CN10], [J18]

Gödel for the win

What makes the difference?

Strong fragments

$I\Sigma_{i+1} \vdash \mathrm{Con}(I\Sigma_i)$

Weak fragments

- $T_2^{i+1} \nvdash \mathrm{Con}(T_2^i)$, in fact:
- [PW87] $EA \nvdash \mathrm{Con}(Q)$!
- [Pud90] $T_2 \nvdash \mathrm{BdCon}(PV_1)$

Can bounded arithmetic prove the consistency of anything?

Propositional proof systems

pps = sound and complete proof system for **CPC** with poly-time recognizable proofs [CR74]

- Frege: textbook system with finitely many axiom schemata and rules
  p-equivalent: sequent calculus, natural deduction
- Extended Frege (EF): may introduce shorthand variables
  p-equivalent: substitution Frege, circuit Frege
- Quantified propositional sequent calculus G: introduction rules for propositional quantifiers
  - G_i: only Σ^q_i cut formulas

$$\exists \vec{x}_1 \, \forall \vec{x}_2 \, \dots \, Q\vec{x}_i \, \underbrace{\theta(\vec{x}_1, \dots, \vec{x}_i, \dots)}_{\text{quantifier-free}}$$

  - G^*, G^*_i: proofs tree-like

Propositional consistency statements

- [Cook75] PV_1 proves $\mathrm{Con}(EF)$
- [KP90] T^i_2 (and S^{i+1}_2) proves $\mathrm{Con}(G_i)$ and $\mathrm{Con}(G^*_{i+1})$

NB: $G_i \ge_p G^*_{i+1}$, $G_i \equiv_p^{\Pi^q_{i+1}} G^*_{i+1}$

Consistency statements = universal sentences (not just Π_1)

Tight correspondence [KP90]

- $PV_1 + \mathrm{Con}(G_i) \equiv \mathrm{Th}_\forall(T^i_2)$
- $T^i_2 \vdash \mathrm{Con}(P) \implies G_i$ p-simulates P (more or less)
- translation of T^i_2 to G_i: see next slide

$\mathrm{Con}(G_i)$ = strongest consistency statement provable in T^i_2

Similarly for S^i_2 and G^*_i (NB: $\mathrm{Th}_\forall(S^i_2) = \mathrm{Th}_\forall(T^{i-1}_2)$)

Propositional translation

[Cook75], [KP90]

- true universal sentence $\forall x\,\theta(x)$
  $\mapsto$ sequence of propositional tautologies $[\![\theta]\!]_n$, $n \in \mathbb{N}$
- true $\forall\Sigma^b_i$ sentence $\forall x\,\theta(x)$
  $\mapsto$ sequence of Σ^q_i tautologies $[\![\theta]\!]_n$
  - if $a_{n-1}\dots a_1 a_0$ binary representation of $a \in \mathbb{N}$:

$$\mathbb{N} \vDash \theta(a) \iff [\![\theta]\!]_n(a_0,\dots,a_{n-1}) \text{ is true}$$

- $T^i_2 \vdash \forall x\,\theta(x) \implies [\![\theta]\!]_n$ have poly-size G_i-proofs
- $S^i_2 \vdash \forall x\,\theta(x) \implies [\![\theta]\!]_n$ have poly-size G^*_i-proofs

$\mathrm{Con}(T)$ vs. $\mathrm{Con}(P)$

$\mathrm{Con}(T)$ same outside as inside:

- $T \overset{?}{\vdash} \mathrm{Con}(T)$ can be diagonalized ($\Longrightarrow$ Gödel's theorem)
  - no obvious way to diagonalize $T \overset{?}{\vdash} \mathrm{Con}(P)$
- $\mathrm{Con}(T)$ can be iterated $\Longrightarrow$ transfinite hierarchy
  - $\mathrm{Con}(P)$ cannot be directly iterated
  - $\mathrm{Th}_\forall(T^i_2)$ finitely axiomatizable while $\mathrm{Th}_\forall(I\Sigma_i)$ reflexive

Possible twist: use $[\![\mathrm{Con}(P)]\!]_n$ inside P?

- usually P has poly-size proofs of $[\![\mathrm{Con}(P)]\!]_n$!
  $\Longrightarrow$ no point in iterating it
- diagonalization prevented by a fixed length-bound

Reflection principles

Relativize consistency statements:

- "X + all true Π_i formulas" consistent
  $\iff$ all Σ_i consequences of X are true

First-order reflection principles

- Local: $\mathrm{Rfn}_\Gamma(T) = \{\Box_T\varphi \to \varphi : \varphi \in \Gamma\}$, $\Gamma = \Sigma_i, \Pi_i$
- Uniform: $\mathrm{RFN}_{\Sigma_i}(T) = \forall\phi \in \Sigma_i\ \big(\Box_T\phi \to \mathrm{Tr}_{\Sigma_i}(\phi)\big)$
  $= \big\{\forall x\, (\Box_T\varphi(\dot{x}) \to \varphi(x)) : \varphi \in \Sigma_i\big\}$

Propositional reflection principles

- $\mathrm{RFN}_i(P) = \forall\phi \in \Sigma_i^q\ \big(\Box_P(\phi) \to \forall e\, (e \vDash_{\Sigma_i^q} \phi)\big)$
- analogue of local reflection?

Characterizing theories by RFN

Strong fragments [Lei83]

- $I\Sigma_i \equiv EA + \mathrm{RFN}_{\Sigma_{i+1}}(EA)$

Weak fragments [KP90]

- $S^i_2 \equiv PV_1 + \mathrm{RFN}_{i+1}(cfG^*) \equiv PV_1 + \mathrm{RFN}_{i+1}(G^*_i)$
- $j \le i$: $\mathrm{Th}_{\forall\Sigma^b_j}(S^i_2) \equiv PV_1 + \mathrm{RFN}_j(G^*_i)$
- $j < i$: $\equiv PV_1 + \mathrm{RFN}_j(G_{i-1})$
- $T^{i-1}_2 \equiv \mathrm{Th}_{\forall\Sigma^b_i}(S^i_2) \equiv PV_1 + \mathrm{RFN}_i(G^*_i)$

NB: propositional translation $\Longrightarrow$ G^*_i and G_{i-1} have poly-size proofs of $[\![\mathrm{RFN}_{i+1}(G^*_i)]\!]_n$ and $[\![\mathrm{RFN}_{i-1}(G_{i-1})]\!]_n$

Finite axiomatizability

Consequences of characterization by RFN:

Strong fragments

- $I\Sigma_i$ itself is finitely axiomatizable
- $j \le i \implies \mathrm{Th}_{\Pi_{j+1}}(I\Sigma_i)$ is reflexive

Weak fragments

- S^i_2, T^i_2 are finitely axiomatizable
- $\mathrm{Th}_{\forall\Sigma^b_j}(S^i_2)$, $\mathrm{Th}_{\forall\Sigma^b_j}(T^i_2)$ finitely axiomatizable for all j

Induction rules

Induction in the form of deduction rules

- Γ-IND^R: $$\frac{\varphi(0) \quad \forall x\,(\varphi(x) \to \varphi(x+1))}{\forall x\,\varphi(x)}$$
- Γ-$PIND^R$: $$\frac{\varphi(0) \quad \forall x\,(\varphi(\lfloor x/2 \rfloor) \to \varphi(x))}{\forall x\,\varphi(x)}$$

$T + R$ = closure of theory T under rule R

$[T, R]$ = closure of T under unnested applications of R

$[T, R]_0 = T$, $[T, R]_{n+1} = [[T, R]_n, R]$: $T + R = \bigcup_n [T, R]_n$

$R \equiv R'$ if $[T, R] = [T, R']$ for every T

Reflection rules

Strong fragments [Bek97]

- $\Sigma_i\text{-}IND^R \equiv \dfrac{\varphi}{\mathrm{RFN}_{\Sigma_i}(EA+\varphi)}$, $\varphi \in \Pi_{i+1}$ over $I\Sigma_{i-1}$
- $\Pi_i\text{-}IND^R \equiv \dfrac{\varphi}{\mathrm{RFN}_{\Sigma_{i-1}}(EA+\varphi)}$, $\varphi \in \Pi_{i+1}$

Weak fragments [J18]

- $\Sigma_i^b\text{-}(P)IND^R \equiv \dfrac{\varphi}{\mathrm{RFN}_i(G_i^{(*)}+\varphi)}$, $\varphi \in \forall\Sigma_i^b$
- $\Pi_i^b\text{-}(P)IND^R \equiv \dfrac{\varphi}{\mathrm{RFN}_{i-1}(G_i^{(*)}+\varphi)}$, $\varphi \in \forall\Sigma_i^b$

$G_i + \forall x\,\theta(x) = G_i$ with axioms $[\![\theta]\!]_n(\vec{A})$, $\vec{A}$ quantifier-free

Parameter-free induction

Consider the induction axiom

$$\varphi(0) \wedge \forall x\, (\varphi(x) \to \varphi(x+1)) \to \forall x\, \varphi(x)$$

- standard induction schemata:
  φ may have arbitrary free variables (parameters)
- parameter-free induction: only x is free in φ

Notation: $I\Gamma^-$, Γ-IND^-, Γ-$PIND^-$

For $\Gamma = \Sigma_i, \Pi_i, \Sigma^b_i, \Pi^b_i$:

- Γ-induction rules equivalent to parameter-free versions
- Γ-$(P)IND^-$ $=$ least theory whose all extensions are closed under Γ-$(P)IND^R$

Parameter-free reflection

Strong fragments [Bek99]

- $I\Sigma_i^- \equiv EA + \{\varphi \to \mathrm{RFN}_{\Sigma_i}(EA + \varphi) : \varphi \in \Pi_{i+1}\}$
- $I\Pi_i^- \equiv EA + \{\varphi \to \mathrm{RFN}_{\Sigma_{i-1}}(EA + \varphi) : \varphi \in \Pi_{i+1}\}$

Weak fragments [J18]

- $\Sigma_i^b\text{-}IND^- \equiv PV_1 + \{\varphi \to \mathrm{RFN}_i(G_i + \varphi) : \varphi \in \forall\Sigma_i^b\}$
- $\Pi_i^b\text{-}IND^- \equiv PV_1 + \{\varphi \to \mathrm{RFN}_{i-1}(G_i + \varphi) : \varphi \in \forall\Sigma_i^b\}$
- the same for $PIND^-$ and G_i^*

Relativized local reflection

Interpret RFN_{Σ_n} as a consistency operator:

- $\langle n \rangle_T \varphi = \mathrm{RFN}_{\Sigma_n}(T + \varphi)$, $[n]_T \varphi = \neg \langle n \rangle_T \neg \varphi$
- $[n] \approx$ provability operator for $T + \mathrm{Th}_{\Pi_n}(\mathbb{N})$
  Hilbert–Bernays–Löb provability conditions
- $\mathrm{Rfn}^n_\Gamma(T) = \{[n]_T \varphi \to \varphi : \varphi \in \Gamma\}$

Restate the previous slide:

Strong fragments [Bek99]

- $I\Sigma_i^- \equiv EA + \mathrm{Rfn}^i_{\Sigma_{i+1}}(EA)$
- $I\Pi_i^- \equiv EA + \mathrm{Rfn}^{i-1}_{\Sigma_{i+1}}(EA)$

Is there a meaningful way to do this for bounded arithmetic?

Finite axiomatizability

Strong fragments [Bek97,99]

For $T \subseteq \Pi_{i+1}$ finite, $\Gamma = \Sigma_i$ or Π_i:

- $[T, \Gamma\text{-}IND^R]_k \subsetneq [T, \Gamma\text{-}IND^R]_{k+1}$
- $T + \Gamma\text{-}IND^R$ reflexive; $I\Sigma_i^-$, $I\Pi_i^-$ reflexive

Weak fragments [J18]

For $T \subseteq \forall\Sigma_i^b$ finite, $\Gamma = \Sigma_i^b$ or Π_i^b:

- $T + \Gamma\text{-}(P)IND^R = [T, \Gamma\text{-}(P)IND^R]$ finitely axiom'ble

Problem

Are $\Sigma_i^b\text{-}(P)IND^-$, $\Pi_i^b\text{-}(P)IND^-$ finitely axiomatizable?

Thank you for attention!

References

- L. D. Beklemishev: Induction rules, reflection principles, and provably recursive functions, Ann. Pure Appl. Logic 85 (1997), 193–242
- ________: Parameter-free induction and provably total computable functions, Theoret. Comput. Sci. 224 (1999), 13–33
- ________: Reflection principles and provability algebras in formal arithmetic, Russian Math. Surveys 60 (2005), 197–268
- S. A. Cook: Feasibly constructive proofs and the propositional calculus, Proc. 7th STOC, 1975, 83–97
- ________, P. Nguyen: Logical foundations of proof complexity, Cambridge University Press, 2010
- ________, R. Reckhow: The relative efficiency of propositional proof systems, J. Symb. Log. 44 (1979), 36–50
- E. Jeřábek: Induction rules in bounded arithmetic, arXiv:1809.10718 [math.LO]
- J. Krajíček: Bounded arithmetic, propositional logic, and complexity theory, Cambridge University Press, 1995
- ________, P. Pudlák: Quantified propositional calculi and fragments of bounded arithmetic, Z. math. Logik Grund. Math. 36 (1990), 29–46
- D. Leivant: The optimality of induction as an axiomatization of arithmetic, J. Symb. Log. 48 (1983), 182–184
- J. B. Paris, A. J. Wilkie: On the scheme of induction for bounded arithmetic formulas, Ann. Pure Appl. Logic 35 (1987), 261–302
- P. Pudlák: A note on bounded arithmetic, Fund. Math. 136 (1990), 86–89