The Reverse Mathematics of Noether's Decomposition Lemma

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Computable Rings

Definition

A *computable ring* is a computable subset $A \subseteq \mathbb{N}$ equipped with two computable binary operations $+$ and $\cdot$ on A, together with elements $0, 1 \in A$ such that $R = (A, 0, 1, +, \cdot)$ is a ring.

All rings will be *countable* and *commutative*, unless we say otherwise.

Noether's Primary Decomposition Lemma

Primary Decomposition Lemma

If R is Noetherian, then R contains only finitely many minimal prime ideals.

Primary Decomposition Lemma

If R contains infinitely many minimal prime ideals, then R is not Noetherian, i.e. R contains an infinite strictly ascending chain of ideals

$$I_0 \subset I_1 \subset I_2 \subset \cdots \subset I_n \subset \cdots \subset R, \ n \in \mathbb{N}.$$

Classical Proof of the Lemma

Assume that R contains infinitely many distinct minimal primes.
Need to construct an infinite strictly ascending chain

$$I_0 \subset I_1 \subset I_2 \subset \cdots I_n \subset \cdots \subset R.$$

Let $I_0 = \langle 0 \rangle_R \subset R$.
Since R contains infinitely many minimal primes, $\langle 0 \rangle_R \subset R$ is not a prime ideal. Therefore there exist $a_1, b_1 \in R$ such that $a_1, b_1 \notin I_0$ but $a_1 b_1 = 0 \in I_0$. Now, either a_1 or b_1 is contained in infinitely many minimal primes; add it to I_0 to get $I_1 \supset I_0$.
Repeat with the invariant that

$$I_k = \langle c_1, c_2, \cdots, c_k \rangle_R \subset R, \;\; k \in \mathbb{N},$$

is contained in infinitely many minimal primes, and therefore is not prime itself. Uses $\emptyset''$.

The "Big Five:"

- RCA_0 : Recursive Comprehension Axiom
- WKL_0 : Weak König's Lemma
- ACA_0 : Arithmetic Comprehension Axiom
- ATR_0 : Arithmetic Transfinite Recursion
- $\Pi^1_1-CA_0$: Π^1_1-Comprehension Axiom

- ADS : Ascending-Descending Chain Principle
- $2-MLR$: Existence of 2-Random sets
- COH : Cohesive set principle
- AMT : Atomic Model Theorem

The Tree Antichain Theorem

Definition

Let $T \subseteq 2^{<\mathbb{N}}$ be a tree. We say that T is completely branching if for all $\sigma \in T$, $\sigma^+ = \{\sigma 0, \sigma 1\} \subset 2^{<\mathbb{N}}$, either

$$\sigma^+ \subset T \quad \text{or} \quad \sigma^+ \cap T = \emptyset.$$

TAC (Tree Antichain Theorem)

Every infinite completely branching computably enumerable tree $T \subseteq 2^{<\mathbb{N}}$ contains an infinite antichain.

TAC (Tree Antichain Theorem–Equivalent Version)

Every infinite tree $T \subseteq 2^{<\mathbb{N}}$ with no terminal nodes and infinitely many splittings has an infinite antichain.

Two Paths to TAC

Fact (RCA_0)

TAC follows from each of 2-MLR and ADS (individually).

Fact (RCA_0)

TAC is restricted Π^1_2.

Fact (RCA_0)

TAC does not follow from WKL

Corollary

TAC is not equivalent to any other "known" subsystem of Second-Order Arithmetic.

Primary Decomposition for Restricted Classes of Rings

Definition

Let R be a ring with multiplicative identity 1_R.

- We say that ideals $I, J \subseteq R$ are <u>coprime</u> whenever $I + J = R$, i.e. $1_R \in I + J$.
- We say that ideals $I, J \subseteq R$ are <u>uniformly coprime</u> if for all $x \in I \cap J$ there exist $y \in I$, $z \in J$, and $a, b \in R$ such that
$$x = yz \quad \text{and} \quad ay + bz = 1_R.$$

Theorem A

If R has infinitely many coprime minimal primes, then R is not Noetherian.

Theorem B

If R has infinitely many uniformly coprime minimal primes, then R is not Noetherian.

Algebraic Characterizations of TAC

Theorem ($RCA_0 + B\Sigma_2$)

Theorem B is equivalent to TAC.

Conjecture ($RCA_0 + B\Sigma_2$)

Theorem A is equivalent to TAC.

TAC implies Theorem B

Given R with infinitely many minimal primes, construct $T = T_R \subseteq 2^{<\mathbb{N}}$ such that:

- every $\sigma \in T$ corresponds to some (zero-divisor) $x_\sigma \in R$;
- $\prod_{\sigma \in S} x_\sigma = 0_R$ whenever S covers $2^{\mathbb{N}}$;
- paths in T correspond to annihilator ideals;
- maximal paths correspond to maximal annihilator (hence minimal prime) ideals.

If $\{\alpha_i : i \in \mathbb{N}\}$ is an infinite $T-$antichain, and

$$I_N = Ann(\prod_{i=1}^{N} x_{\alpha_i}),$$

then

$$I_0 \subset I_1 \subset I_2 \cdots \subset I_N \subset \cdots .$$

Theorem B implies TAC

Given infinite Σ_1^0 completely branching $T \subseteq 2^{<\mathbb{N}}$.
Construct R via:

- R is a quotient of $\mathbb{Q}[X_\sigma : \sigma \in T]$ such that
  - $X_\emptyset = 0 \in R$,
  - $X_{\sigma 0} X_{\sigma 1} = X_\sigma$, and
  - inverses for all polynomials such that the intersection of the partial$-2^{\mathbb{N}}-$coverings yielded by the monomials is empty.
- R is a PIR; every ideal $I \subset R$ is generated by a monomial.
- Given an infinite strictly ascending $R-$chain, one can effectively find a principle generator for each ideal in the chain and use $\mathrm{B}\Sigma_2$ along with the sequence of exponents of these generators to build an infinite antichain of T in the context.

First-Order Considerations

Over RCA_0 we have that TAC $\rightarrow$ Theorem B.
The converse follows from $\mathrm{RCA}_0 + \mathrm{B}\Sigma_2$.

Definition (RCA_0)

For each $n \in \mathbb{N}$, let $n-$TAC be the principle that says "for every infinite tree $T \subseteq 2^{<\mathbb{N}}$ with infinitely many splittings, there is a (path-)nonincreasing $f_T : T \rightarrow \mathbb{N}$ such that:

- $f(\emptyset) = n$;
- there exist infinitely many $\sigma \in T$ and $i_\sigma \in \{0, 1\}$ such that:

$$f(\sigma) > f(\sigma i_\sigma).$$

TAC is equivalent to 1-TAC. Let WTAC be $n-$TAC without the n.

TAC $\longrightarrow$ Theorem B $\longrightarrow$ WTAC, over RCA_0.
TAC $\longleftrightarrow$ Theorem A/B $\longleftrightarrow$ WTAC, over $\mathrm{RCA}_0 + \mathrm{B}\Sigma$.
Q: What is the first order part of $n-$TAC, WTAC?

Consequences of the Hilbert Basis Theorem: The Krull Intersection Theorem

Theorem (Krull Intersection Theorem; KIT)

If R is an integral domain, $I \subset R$ an ideal, then

$$\bigcap_{n \in \mathbb{N}} I^n = 0_R.$$

Theorem (RCA_0, Conidis (2021))

KIT implies WKL_0.

The Primary Decomposition Lemma

We need to use infinite combinatorial structures (graphs) that are more general than trees and include (undirected) cycles.

Theorem

The Primary Decomposition Lemma follows from CAC+WKL_0.

Lemma (RCA_0)

- *If R is Noetherian, then the nilradical $N \subset R$ exists and $N^n = 0_R$, for some $n \in \mathbb{N}$.*
- *PDL implies KIT (and thus WKL_0).*

Conjecture (RCA_0)

The Primary Decomposition Lemma implies:

- *KIT; (Milne's Lecture Notes; online)*
- *WKL_0;*
- *TAC+WKL_0.*

Thank You!