

Reverse mathematics, Young diagrams, and the ascending chain condition

Kostas Hatzikiriakou
Department of Primary Education
University of Thessaly
Argonafton & Filellinon
Volos 38221, GREECE
kxatzkyr@uth.gr

Stephen G. Simpson
Department of Mathematics
Pennsylvania State University
State College, PA 16802, USA
<http://www.math.psu.edu/simpson>
simpson@math.psu.edu

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Abstract

Let S be the group of finitely supported permutations of a countably infinite set. Let $K[S]$ be the group algebra of S over a field K of characteristic 0. According to a theorem of Formanek and Lawrence, $K[S]$ satisfies the ascending chain condition for two-sided ideals. We study the reverse mathematics of this theorem, proving its equivalence over \mathbf{RCA}_0 (or even over \mathbf{RCA}_0^*) to the statement that ω^ω is well ordered. Our equivalence proof proceeds via the statement that the Young diagrams form a well partial ordering.

Keywords: reverse mathematics, ascending chain condition, group rings, Young diagrams, partition theory, well partial orderings.

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Contents

1	Introduction	2
2	Well partial ordering of diagrams	4
3	Closed sets of diagrams	6
4	Two-sided ideals in $K[S]$	9
5	Weakening the base theory	10
6	A question for future research	12
	References	12

1 Introduction

Reverse mathematics is a research program in the foundations of mathematics. The purpose of reverse mathematics is to discover which axioms are needed to prove specific core-mathematical theorems of analysis, algebra, geometry, combinatorics, etc. Reverse mathematics takes place in the context of subsystems of second-order arithmetic. The standard reference for reverse mathematics is [26, Part A]. This paper is a contribution to the reverse mathematics of algebra.

Let \mathbb{Q} be the field of rational numbers. The *Hilbert Basis Theorem* [11] says that, for each positive integer n , there is no infinite ascending sequence of ideals in the polynomial ring $\mathbb{Q}[x_1, \dots, x_n]$. This is one of the most famous theorems of abstract algebra. In a previous paper [24, Theorem 2.7] we have shown that the Hilbert Basis Theorem¹ is reverse-mathematically equivalent to $\text{WO}(\omega^\omega)$. Here $\text{WO}(\omega^\omega)$ is the assertion that (the standard system of Cantor normal form notations for the ordinal numbers less than the ordinal number) ω^ω is well ordered. The place of $\text{WO}(\omega^\omega)$ within the usual hierarchy of subsystems of second-order arithmetic [26] is discussed in the expository paper [30].

Our reverse-mathematical result in [24, Theorem 2.7] implies that the Hilbert Basis Theorem is not finitistically reducible. (See [24, Proposition 2.6].) This foundational outcome is significant with respect to Hilbert's foundational program of finitistic reductionism [12, 25, 33]. In a certain fairly precise philosophical sense [28, 29], our result in [24, Theorem 2.7] justifies Gordan's famous remark (see [18]) to the effect that the Hilbert Basis Theorem is not mathematics but rather theology.

On the other hand, in analyzing the significance of [24, Theorem 2.7], it is important to note that the Hilbert Basis Theorem refers not to a single ring but to a sequence of rings $\mathbb{Q}[x_1, \dots, x_n]$ where $n = 1, 2, 3, \dots$. Moreover, for each specific positive integer n , the special case $\mathbb{Q}[x_1, \dots, x_n]$ of the Hilbert Basis Theorem is finitistically reducible, in fact provable in RCA_0 [24, Lemmas 3.4 and 3.6]. Therefore, from the foundational viewpoint of [24, §1], it would be interesting to find a specific commutative ring which has no infinite ascending sequence of ideals and to prove that the corresponding basis theorem is not finitistically reducible.

¹A related theorem of Hilbert says that for each n there is no infinite ascending sequence of ideals in the power series ring $\mathbb{Q}[[x_1, \dots, x_n]]$. We have shown in [10] that this theorem, like the Hilbert Basis Theorem, is reverse-mathematically equivalent to $\text{WO}(\omega^\omega)$.

At the moment we are unable to provide such a commutative ring, but in this paper we achieve something similar in the noncommutative case. Specifically, we perform a reverse-mathematical analysis of a theorem of Formanek and Lawrence [6]. The *Formanek/Lawrence Theorem* says that there is no infinite ascending sequence of two-sided ideals in the group algebra $\mathbb{Q}[S]$ of the infinite symmetric group S over the field \mathbb{Q} . The purpose of this paper is to show that the Formanek/Lawrence Theorem, like the Hilbert Basis Theorem, is reverse-mathematically equivalent to $\text{WO}(\omega^\omega)$. From this result it follows, just as in [24], that the Formanek/Lawrence Theorem is not finitistically reducible.

Our work in this paper involves partitions. A *partition* is a finite sequence of integers m_1, \dots, m_k such that $m_1 \geq \dots \geq m_k > 0$ and $k > 0$. It is well known (see for instance [4, §28]) that there is a close relationship between two-sided ideals in $\mathbb{Q}[S]$ and partitions. A partition m_1, \dots, m_k is usually visualized as a *Young diagram*, i.e., a planar array of boxes with k left-justified rows of lengths m_1, \dots, m_k respectively. For example, the partition $5, 2, 2, 1$ is visualized as the Young diagram in Figure 1 consisting of $10 = 5 + 2 + 2 + 1$ boxes. Note that there is another partition $4, 3, 1, 1, 1$ consisting of the lengths of the columns of this same Young diagram. A standard reference for partition theory is [1].

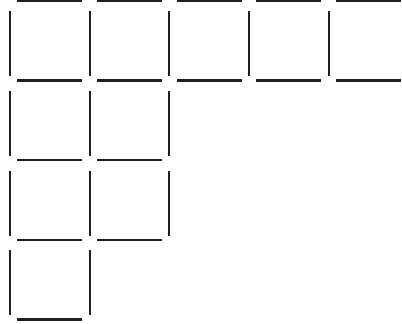


Figure 1: The Young diagram corresponding to the partition $5, 2, 2, 1$.

Our notation and terminology in this paper is as follows. We use \mathbb{N} to denote the set of positive integers. We use i, j, k, l, m, n as variables ranging over \mathbb{N} . We use \mathcal{D} to denote the set of *diagrams*, i.e., Young diagrams. We use D, E, F, G, H as variables ranging over \mathcal{D} . Given $D \in \mathcal{D}$, the number of boxes in D is denoted $|D|$. We write $r_i(D)$ = the length of the i th row of D , or 0 if $i >$ the number of rows. Similarly, we write $c_i(D)$ = the length of the i th column of D , or 0 if $i >$ the number of columns. Note that $|D| = r_1(D) + \dots + r_k(D) = c_1(D) + \dots + c_l(D)$ where $k = c_1(D) = \max(\{i \mid r_i(D) > 0\})$ = the number of rows, and $l = r_1(D) = \max(\{i \mid c_i(D) > 0\})$ = the number of columns. Note also that $|D| \leq r_1(D) \cdot c_1(D)$. For $D, E \in \mathcal{D}$ we write $D \leq E$ to mean that $r_i(D) \leq r_i(E)$ for all i , or equivalently $c_i(D) \leq c_i(E)$ for all i . Thus \mathcal{D}, \leq is a partial ordering. We write $D < E$ to mean that $D \leq E$ and $D \neq E$. We write $D \cup E = \sup(D, E)$ = the unique diagram F such that $r_i(F) = \max(r_i(D), r_i(E))$ for all i , or equivalently $c_i(F) = \max(c_i(D), c_i(E))$ for all i .

As in [24] some of our results in this paper involve well partial ordering theory.

A *well partial ordering* is a partial ordering \mathcal{P}, \leq such that for all infinite sequences $\langle P_i \rangle_{i \in \mathbb{N}}$ of elements of \mathcal{P} there exist $i, j \in \mathbb{N}$ such that $i < j$ and $P_i \leq P_j$. For example, any well ordering is a well partial ordering, and the product of any two well partial orderings is a well partial ordering. For background on well partial ordering theory, see [5, 20, 22, 23, 34]. A key fact for us in this paper is that \mathcal{D}, \leq is a well partial ordering. We denote this fact as $\text{WPO}(\mathcal{D})$. In Theorem 2.6 we show that the statement $\text{WPO}(\mathcal{D})$ is robust with respect to equivalence over RCA_0 .

The plan of this paper is as follows. In §2 we prove that the statements $\text{WO}(\omega^\omega)$ and $\text{WPO}(\mathcal{D})$ are equivalent over RCA_0 . In §3 we define what it means for a subset of \mathcal{D} to be *closed*, and we prove that $\text{WPO}(\mathcal{D})$ is equivalent over RCA_0 to the statement that there is no infinite ascending sequence of closed subsets of \mathcal{D} . In §4 we show that the latter statement is equivalent over RCA_0 to the statement that there is no infinite ascending sequence of two-sided ideals in $\mathbb{Q}[S]$. Combining this with the results of §2 and §3, we obtain our main result. In §5 we show how the base theory RCA_0 can be weakened to RCA_0^* . In §6 we raise a question for future research.

2 Well partial ordering of diagrams

In this section we use a result from [24] to prove in RCA_0 that the set \mathcal{D} of all diagrams is well partially ordered if and only if the ordinal number ω^ω is well ordered.

Lemma 2.1. RCA_0 proves $\text{WO}(\omega^\omega) \Rightarrow \text{WPO}(\mathcal{D})$.

Proof. Reasoning in RCA_0 , assume that $\text{WPO}(\mathcal{D})$ fails, i.e., \mathcal{D} is not well partially ordered. Let $\langle D_i \rangle_{i \in \mathbb{N}}$ be a *bad sequence* of diagrams, i.e., $\forall i \forall j (i < j \Rightarrow D_i \not\leq D_j)$. Let $m = r_1(D_1)$ and $n = c_1(D_1)$. For all $j > 1$ we have $D_1 \not\leq D_j$, hence $m > r_n(D_j)$ and $n > c_m(D_j)$. To each diagram D such that $m > r_n(D)$ and $n > c_m(D)$, we associate a sequence $s(D) \in \mathbb{N}^{m+n-2}$ given by

$$s(D) = \langle r_1(D) + 1, \dots, r_{n-1}(D) + 1, c_1(D) + 1, \dots, c_{m-1}(D) + 1 \rangle.$$

The point is that for any two such diagrams D and E , we have $D \leq E$ if and only if $s(D) \leq s(E)$ with respect to the coordinatewise partial ordering of \mathbb{N}^{m+n-2} . Since $\langle D_j \rangle_{j > 1}$ is a bad sequence of diagrams, it follows that $\langle s(D_j) \rangle_{j > 1}$ is a bad sequence in \mathbb{N}^{m+n-2} , hence \mathbb{N}^{m+n-2} is not well partially ordered. It then follows by [24, Lemma 3.6] that ω^ω is not well ordered, i.e., $\text{WO}(\omega^\omega)$ fails. \square

Lemma 2.2. RCA_0 proves $\text{WPO}(\mathcal{D}) \Rightarrow \text{WO}(\omega^\omega)$.

Proof. We reason in RCA_0 . Given a nonzero ordinal $\alpha < \omega^\omega$, write α in Cantor normal form as $\alpha = \omega^{n_1} + \dots + \omega^{n_k}$ where $n_1 \geq \dots \geq n_k \geq 0$ and $k > 0$. Let $D(\alpha)$ be the unique diagram D with $r_1(D) = n_1 + 1, \dots, r_k(D) = n_k + 1$ and $r_{k+1}(D) = 0$. Clearly $D(\alpha) \leq D(\beta)$ implies $\alpha \leq \beta$. Assume now that $\text{WO}(\omega^\omega)$ fails. Let $\langle \alpha_i \rangle_{i \in \mathbb{N}}$ be an infinite descending sequence of ordinals $< \omega^\omega$, i.e., $\omega^\omega > \alpha_i > \alpha_j$ for all $i, j \in \mathbb{N}$ such that $i < j$. Then $D(\alpha_i) \not\leq D(\alpha_j)$ for all $i, j \in \mathbb{N}$ such that $i < j$, hence $\langle D(\alpha_i) \rangle_{i \in \mathbb{N}}$ is a bad sequence in \mathcal{D} , so $\text{WPO}(\mathcal{D})$ fails. \square

Theorem 2.3. RCA_0 proves $\text{WPO}(\mathcal{D}) \Leftrightarrow \text{WO}(\omega^\omega)$.

Proof. This is immediate from Lemmas 2.1 and 2.2. \square

As a technical supplement to Theorem 2.3, we now prove a theorem to the effect that the statement $\text{WPO}(\mathcal{D})$ is robust up to equivalence over RCA_0 .

Definition 2.4. Within RCA_0 we make the following definitions.

1. A set \mathcal{U} of diagrams is said to be *upwardly closed* if $\forall D \forall E ((D \in \mathcal{U} \text{ and } D \leq E) \Rightarrow E \in \mathcal{U})$. For each finite set \mathcal{S} of diagrams, there exists a set $\text{ucl}(\mathcal{S}) = \{E \mid \exists D (D \in \mathcal{S} \text{ and } D \leq E)\}$ = the *upward closure* of \mathcal{S} , i.e., the smallest upwardly closed set which includes \mathcal{S} . An upwardly closed set of diagrams is *finitely generated* if it is of the form $\text{ucl}(\mathcal{S})$ for some finite set \mathcal{S} .
2. Consider a sequence of diagrams $\langle D_i \rangle_{i \in \mathbb{N}}$. The sequence is said to be *upwardly closed* if $\forall i \forall E (D_i \leq E \Rightarrow \exists j (D_j = E))$. The sequence is said to be *finitely generated* if there is a finite set \mathcal{S} such that $\forall E (E \in \text{ucl}(\mathcal{S}) \Leftrightarrow \exists j (D_j = E))$, i.e., there is a finitely generated, upwardly closed set which is the range of the sequence.

Lemma 2.5. RCA_0 proves the following. If all upwardly closed sets of diagrams are finitely generated, then all upwardly closed sequences of diagrams are finitely generated.

Proof. We reason in RCA_0 . Let $\langle D_i \rangle_{i \in \mathbb{N}}$ be an upwardly closed sequence of diagrams which is not finitely generated. Define a subsequence $\langle D_{i_n} \rangle_{i_n \in \mathbb{N}}$ recursively as follows. Let $i_1 = 1$. Given $i_1 < \dots < i_n$ let i_{n+1} = the least $i > i_n$ such that $D_i \notin \text{ucl}(\{D_{i_1}, \dots, D_{i_n}\})$ and $|D_i| > \max(|D_{i_1}|, \dots, |D_{i_n}|)$. Thus $i_n < i_{n+1}$ and $|D_{i_n}| < |D_{i_{n+1}}|$ for all n . By Δ_1^0 comprehension let \mathcal{U} be the set of diagrams D such that $D \in \text{ucl}(\{D_{i_1}, \dots, D_{i_n}\})$ where n = the least n such that $|D_{i_n}| > |D|$. Clearly $\mathcal{U} = \bigcup_{n \in \mathbb{N}} \text{ucl}(\{D_{i_1}, \dots, D_{i_n}\})$, hence \mathcal{U} is upwardly closed, and $\mathcal{U} \neq \text{ucl}(\{D_{i_1}, \dots, D_{i_n}\})$ for all n , hence \mathcal{U} is not finitely generated. \square

Theorem 2.6. Over RCA_0 each of the following statements implies the others.

1. $\text{WPO}(\mathcal{D})$.
2. There is no infinite ascending sequence of upwardly closed sets of diagrams.
3. There is no infinite ascending sequence of finitely generated, upwardly closed sets of diagrams.
4. Every upwardly closed set of diagrams is finitely generated.
5. Every upwardly closed sequence of diagrams is finitely generated.

Proof. We reason in RCA_0 . To prove $1 \Rightarrow 2$, assume that 2 fails. Let $\langle \mathcal{U}_i \rangle_{i \in \mathbb{N}}$ be an infinite ascending sequence of upwardly closed sets of diagrams. For each i let D_i be the least element of $\mathcal{U}_{i+1} \setminus \mathcal{U}_i$. Then $\langle D_i \rangle_{i \in \mathbb{N}}$ is a bad sequence of diagrams, so 1 fails.

Trivially $2 \Rightarrow 3$. To prove $3 \Rightarrow 4$, assume that 4 fails. Let \mathcal{U} be an upwardly closed set of diagrams which is not finitely generated. Let D_1 be the least element of \mathcal{U} . Given $D_1, \dots, D_n \in \mathcal{U}$, let D_{n+1} = the least element of $\mathcal{U} \setminus \mathcal{U}_n$ where $\mathcal{U}_n = \text{ucl}(\{D_1, \dots, D_n\})$. Then $\langle \mathcal{U}_n \rangle_{n \in \mathbb{N}}$ is an infinite ascending sequence of upwardly closed sets, so 3 fails.

By Lemma 2.5 we have $4 \Rightarrow 5$. It remains to prove $5 \Rightarrow 1$. Assume that 1 fails. Let $\langle D_i \rangle_{i \in \mathbb{N}}$ be a bad sequence of diagrams. The formula $\Phi(E) \equiv \exists i (D_i \leq E)$ is Σ_1^0 , so by [26, Lemma II.3.7] there is a sequence of diagrams $\langle E_j \rangle_{j \in \mathbb{N}}$ such that $\forall E (\Phi(E) \Leftrightarrow \exists j (E = E_j))$. Clearly $\langle E_j \rangle_{j \in \mathbb{N}}$ is an upwardly closed sequence of diagrams, and by Σ_1^0 bounding we have $\forall m \exists n (\forall j < m) (\exists i < n) (D_i \leq E_j)$. Because $\langle D_i \rangle_{i \in \mathbb{N}}$ is bad, it follows that $\langle E_j \rangle_{j \in \mathbb{N}}$ is not finitely generated, so 5 fails. This completes the proof. \square

3 Closed sets of diagrams

Definition 3.1. A set \mathcal{U} of diagrams is said to be *closed* if

$$\forall D (D \in \mathcal{U} \Leftrightarrow \forall E (E > D \Rightarrow E \in \mathcal{U})).$$

Remark 3.2. Obviously all closed sets of diagrams are upwardly closed. However, not all upwardly closed sets of diagrams are closed. For example, letting D and E be the diagrams corresponding to the partitions 4, 2 and 2, 2, 1, 1 respectively, the upwardly closed set $\text{ucl}(\{D, E\})$ is not closed. In this section we clarify the structure of closed sets of diagrams. Definition 3.3 and Lemmas 3.4–3.6 and Theorem 3.8 appear to be new, in the sense that we have not found their counterparts in the partition theory literature such as [1, 4, 6, 7].

Definition 3.3. Given a diagram D , let $(D)_r$ = the diagram obtained by shortening the first row to the length of the second row, or 1 if there is no second row. Thus $r_1((D)_r) = \max(r_2(D), 1)$ and $r_i((D)_r) = r_i(D)$ for all $i > 1$. Similarly, let $(D)_c$ = the diagram obtained by shortening the first column to the length of the second column, or 1 if there is no second column. Thus $c_1((D)_c) = \max(c_2(D), 1)$ and $c_i((D)_c) = c_i(D)$ for all $i > 1$.

The next three lemmas are proved in RCA_0 .

Lemma 3.4. For all diagrams D we have $D = (D)_r \cup (D)_c$. For all diagrams D and E , if $(D)_r = (E)_r$ or $(D)_c = (E)_c$, then $D \leq E$ or $E \leq D$.

Proof. These statements are obvious from Definition 3.3. \square

Lemma 3.5. Let D, E, F be diagrams such that $|F| > (r_1(D) - 1)(c_1(E) - 1)$ and $F \geq (D)_r \cup (E)_c$. Then $F \geq D$ or $F \geq E$.

Proof. Since $|F| > (r_1(D) - 1)(c_1(E) - 1)$, we must have $r_1(F) \geq r_1(D)$ or $c_1(F) \geq c_1(E)$. In the first case we have $F \geq (\text{first row of } D)$ and $F \geq (D)_r$, hence $F \geq D$. In the second case we have $F \geq (\text{first column of } E)$ and $F \geq (E)_c$, hence $F \geq E$. \square

Lemma 3.6. Let \mathcal{S} be a finite set of diagrams. Suppose F is a diagram such that $\exists n \forall G ((|G| > n \text{ and } G > F) \Rightarrow G \in \text{ucl}(\mathcal{S}))$. Then $F \geq (D)_r \cup (E)_c$ for some $D, E \in \mathcal{S}$.

Proof. Let \mathcal{S} and F and n be as in the hypothesis. Since \mathcal{S} is finite, we may safely assume that $n > \max(|F|, \max(\{r_1(D), c_1(E) \mid D, E \in \mathcal{S}\}))$. Let G be the unique diagram with $r_1(G) = n + 1$ and $r_i(G) = r_i(F)$ for all $i > 1$. Then $G > F$ and $|G| > n$, hence $G \in \text{ucl}(\mathcal{S})$, i.e., $G \geq D$ for some $D \in \mathcal{S}$. It then follows that $F \geq (D)_r$. Similarly, let H be the unique diagram with $c_1(H) = n + 1$ and $c_i(H) = c_i(F)$ for all $i > 1$, then $H \geq E$ for some $E \in \mathcal{S}$, hence $F \geq (E)_c$. Thus $F \geq (D)_r \cup (E)_c$. \square

Definition 3.7. Given a finite set \mathcal{S} of diagrams, let

$$\widehat{\mathcal{S}} = \{(D)_r \cup (E)_c \mid D, E \in \mathcal{S}\},$$

and let

$$\overline{\mathcal{S}} = \{F \in \text{ucl}(\widehat{\mathcal{S}}) \mid |F| \leq \|\mathcal{S}\|\}$$

where

$$\|\mathcal{S}\| = \max(\{(r_1(D) - 1)(c_1(E) - 1) \mid D, E \in \mathcal{S}\}).$$

Note that $\widehat{\mathcal{S}}$ and $\overline{\mathcal{S}}$ are finite sets of diagrams, and they can be found effectively given the finite set \mathcal{S} . Note also that $\mathcal{S} \subseteq \widehat{\mathcal{S}}$, hence $\text{ucl}(\mathcal{S}) \subseteq \text{ucl}(\widehat{\mathcal{S}})$.

Theorem 3.8. RCA_0 proves the following. For any finite set \mathcal{S} of diagrams, we have $\text{ucl}(\widehat{\mathcal{S}}) = \overline{\mathcal{S}} \cup \text{ucl}(\mathcal{S})$. Moreover, $\text{ucl}(\widehat{\mathcal{S}})$ is closed and includes \mathcal{S} and is included in all closed sets that include \mathcal{S} .

Proof. Trivially $\overline{\mathcal{S}} \cup \text{ucl}(\mathcal{S}) \subseteq \text{ucl}(\widehat{\mathcal{S}})$, and by Lemma 3.5 we have $\text{ucl}(\widehat{\mathcal{S}}) \subseteq \overline{\mathcal{S}} \cup \text{ucl}(\mathcal{S})$, so $\text{ucl}(\widehat{\mathcal{S}}) = \overline{\mathcal{S}} \cup \text{ucl}(\mathcal{S})$. Also by Lemma 3.5, for any closed set \mathcal{U} such that $\mathcal{S} \subseteq \mathcal{U}$ we have $\widehat{\mathcal{S}} \subseteq \mathcal{U}$, hence $\text{ucl}(\widehat{\mathcal{S}}) \subseteq \mathcal{U}$. It remains to prove that $\text{ucl}(\widehat{\mathcal{S}})$ is closed. Let F be a diagram such that $\forall G (G > F \Rightarrow G \in \text{ucl}(\widehat{\mathcal{S}}))$, i.e., $\forall G (G > F \Rightarrow G \in \overline{\mathcal{S}} \cup \text{ucl}(\mathcal{S}))$. From the definition of $\overline{\mathcal{S}}$ it follows that $\forall G ((\|G\| > \|\mathcal{S}\| \text{ and } G > F) \Rightarrow G \in \text{ucl}(\mathcal{S}))$. But then by Lemma 3.6 we have $F \in \text{ucl}(\widehat{\mathcal{S}})$. Thus $\text{ucl}(\widehat{\mathcal{S}})$ is closed, Q.E.D. \square

We shall now use Theorem 3.8 to prove a result about closed sets of diagrams which is analogous to Theorem 2.6 about upwardly closed sets of diagrams. Our result here will be needed in §4.

Definition 3.9. Within RCA_0 we make the following definitions.

1. The *closure* of a finite set \mathcal{S} of diagrams is the set

$$\text{cl}(\mathcal{S}) = \text{ucl}(\widehat{\mathcal{S}}) = \overline{\mathcal{S}} \cup \text{ucl}(\mathcal{S}).$$

This definition is appropriate in view of Definition 3.7 and Theorem 3.8.

2. A sequence of diagrams $\langle D_i \rangle_{i \in \mathbb{N}}$ is said to be *closed* if $\forall D ((\exists i (D = D_i)) \Leftrightarrow \forall E (E > D \Rightarrow \exists j (E = D_j)))$.

Remark 3.10. Theorem 3.8 implies that a closed set of diagrams is finitely generated qua closed set if and only if it is finitely generated qua upwardly closed set, i.e., finitely generated in the sense of Definition 2.4. And similarly, a closed sequence of diagrams is finitely generated qua closed sequence if and only if it is finitely generated qua upwardly closed sequence.

Lemma 3.11. RCA_0 proves the following. Given a closed sequence of diagrams $\langle D_i \rangle_{i \in \mathbb{N}}$ which is not finitely generated, we can find a subsequence $\langle D_{i_n} \rangle_{n \in \mathbb{N}}$ such that $\forall n (D_{i_n} \notin \text{cl}(\{D_{i_1}, \dots, D_{i_{n-1}}\}))$ and $\forall m \forall n (m < n \Rightarrow D_{i_n} \not\leq D_{i_m})$.

Proof. We reason in RCA_0 . Using the results of [26, §II.3], define i_n recursively as follows. Let $i_1 = 1$. Assume inductively that $i_1 < \dots < i_n$ have been defined. By bounded Σ_1^0 comprehension [26, Theorem II.3.9] there is a finite set $\mathcal{T}_n = \{D \mid \exists j \exists m (D = D_j \text{ and } m \leq n \text{ and } D \leq D_{i_m})\}$. Since $\langle D_i \rangle_{i \in \mathbb{N}}$ is not finitely generated, we have $D_i \notin \text{cl}(\mathcal{T}_n)$ for infinitely many i . Let i_{n+1} = the least such i which is also $> i_n$. Clearly the subsequence $\langle D_{i_n} \rangle_{n \in \mathbb{N}}$ has the desired properties. \square

Lemma 3.12. RCA_0 proves the following. If all closed sets of diagrams are finitely generated, then all closed sequences of diagrams are finitely generated.

Proof. We reason in RCA_0 . Suppose there is a closed sequence of diagrams which is not finitely generated. By Lemma 3.11 let $\langle D_n \rangle_{n \in \mathbb{N}}$ be a sequence of diagrams such that $\forall n (D_n \notin \text{cl}(\{D_1, \dots, D_{n-1}\}))$ and $\forall m \forall n (m < n \Rightarrow D_n \not\leq D_m)$. In particular

we have $\forall m \forall n (D_m \leq D_n \Rightarrow m = n)$. It follows by Lemma 3.4 that for all D , there is at most one n such that $(D_n)_r = D$ and there is at most one n such that $(D_n)_c = D$.

Using the results of [26, §II.3] define a subsequence $\langle D_{n_k} \rangle_{k \in \mathbb{N}}$ recursively as follows. Assume inductively that $n_1 < \dots < n_{k-1}$ have been defined. Let $S_k = \{D_{n_1}, \dots, D_{n_{k-1}}\}$. The set of diagrams D such that $|D| \leq \|S_k\|$ is finite, so by bounded Σ_1^0 comprehension and Σ_1^0 bounding we have $|(D_n)_r| > \|S_k\|$ and $|(D_n)_c| > \|S_k\|$ for all sufficiently large n . Let n_k = the least such n which is also $> n_{k-1}$. This completes the construction. The construction insures that $\forall k \forall l \forall D$ (if $k < l$ and $D \in \text{cl}(S_l)$ and $|D| \leq \|S_k\|$ then $D \in \text{cl}(S_k)$).

By Δ_1^0 comprehension let \mathcal{U} be the set of diagrams D such that $D \in \text{cl}(S_k)$ where k = the least k such that $|D| \leq \|S_k\|$. Then $\mathcal{U} = \bigcup_{k \in \mathbb{N}} \text{cl}(S_k)$ is a closed set of diagrams which not finitely generated. This proves our lemma. \square

Theorem 3.13. Over RCA_0 each of the following statements implies the others.

1. $\text{WPO}(\mathcal{D})$.
2. There is no infinite ascending sequence of closed sets of diagrams.
3. There is no infinite ascending sequence of finitely generated closed sets of diagrams.
4. Every closed set of diagrams is finitely generated.
5. Every closed sequence of diagrams is finitely generated.

Proof. We reason in RCA_0 . Let D be a diagram, and let \mathcal{S} be a finite set of diagrams. By Theorem 3.8 and Definition 3.9, the relation $D \in \text{cl}(\mathcal{S})$ is Δ_1^0 . With this remark in mind, the proofs of $1 \Rightarrow 2$ and $2 \Rightarrow 3$ and $3 \Rightarrow 4$ are similar to the proofs of the corresponding implications in Theorem 2.6.

By Lemma 3.12 we have $4 \Rightarrow 5$. It remains to prove $5 \Rightarrow 1$. Assume that 1 fails. Let $\langle D_i \rangle_{i \in \mathbb{N}}$ be a bad sequence of diagrams. The formula $\Phi(E) \equiv \exists i (E \in \text{cl}(\{D_1, \dots, D_i\}))$ is Σ_1^0 , so by [26, Lemma II.3.7] there is a sequence of diagrams $\langle E_j \rangle_{j \in \mathbb{N}}$ such that $\forall E (\Phi(E) \Leftrightarrow \exists j (E = E_j))$. Clearly $\langle E_j \rangle_{j \in \mathbb{N}}$ is closed. We claim that $\langle E_j \rangle_{j \in \mathbb{N}}$ is not finitely generated. Otherwise, by Σ_1^0 bounding there would be an n such that $\{D_1, \dots, D_n\}$ is a set of generators. Let $\mathcal{S} = \{D_1, \dots, D_n\}$. By Theorem 3.8 and Definition 3.9 we have $\text{cl}(\mathcal{S}) = \overline{\mathcal{S}} \cup \text{ucl}(\mathcal{S})$. Since $\overline{\mathcal{S}}$ is finite we have $D_i \notin \overline{\mathcal{S}}$ for all sufficiently large i , and since $\langle D_i \rangle_{i \in \mathbb{N}}$ is bad we have $D_i \notin \text{ucl}(\mathcal{S})$ for all $i > n$. It is now clear that $D_i \notin \text{cl}(\mathcal{S})$ for all sufficiently large i , contradicting our assumption that \mathcal{S} is a set of generators. Thus $\langle E_j \rangle_{j \in \mathbb{N}}$ is a counterexample to 5, so 5 fails, Q.E.D. \square

Remark 3.14. For each $n \in \mathbb{N}$ let \mathcal{D}_n be the set of nonempty finite subsets of \mathbb{N}^n which are downwardly closed with respect to the coordinatewise partial ordering of \mathbb{N}^n . It is known that \mathcal{D}_n is well partially ordered under inclusion. Recall that Figure 1 is the diagram corresponding to the partition 5, 2, 2, 1. If we rotate Figure 1 counterclockwise by $3\pi/4$ radians, we obtain a picture of an element of \mathcal{D}_2 , namely, the downwardly closed subset of \mathbb{N}^2 consisting of 10 elements:

$$(1, 1), (1, 2), (1, 3), (1, 4), (1, 5), (2, 1), (2, 2), (3, 1), (3, 2), (4, 1).$$

In this way we obtain a one-to-one order-preserving correspondence between \mathcal{D}_2 and \mathcal{D} . Similarly, there is a one-to-one order-preserving correspondence between \mathcal{D}_{n+1} and the so-called n -dimensional partitions which are discussed in [1, Chapter 11]. Our results in this section may be interpreted as results about \mathcal{D}_2 , and it is straightforward to generalize them to \mathcal{D}_{n+1} . It would be interesting to find appropriate similar generalizations of our results in §2, from \mathcal{D}_2 to \mathcal{D}_{n+1} .

4 Two-sided ideals in $K[S]$

In this section we review the known one-to-one correspondence [6, Theorem 2] between closed sets of diagrams and two-sided ideals of $K[S]$. We observe that this correspondence is provable in RCA_0 . We use this observation plus our Theorems 2.3 and 3.13 to obtain a reverse-mathematical classification of the known theorem [6, Theorem 10] that $K[S]$ satisfies the ascending chain condition for two-sided ideals.

Definition 4.1. The following definitions are made in RCA_0 .

1. Let S be the *infinite symmetric group*, i.e., the group of finitely supported permutations of \mathbb{N} . Let K be a countable field of characteristic 0. For instance, we could take $K = \mathbb{Q}$. The *group algebra* $K[S]$ is the set of formal finite linear combinations $\sum_g a_g g$ where $g \in S$, $a_g \in K$, and $a_g = 0$ for all but finitely many $g \in S$. The algebraic operations on $K[S]$ are given by

$$\begin{aligned} c \sum_g a_g g &= \sum_g (ca_g) g, \\ \sum_g a_g g + \sum_g b_g g &= \sum_g (a_g + b_g) g, \\ \sum_g a_g g \cdot \sum_g b_g g &= \sum_g \sum_h (a_g b_h)(gh). \end{aligned}$$

2. A *two-sided ideal* of $K[S]$ is a nonempty set $\mathcal{I} \subseteq K[S]$ such that $(\forall p \in \mathcal{I}) (\forall q \in \mathcal{I}) (p + q \in \mathcal{I})$ and $(\forall p \in \mathcal{I}) (\forall r \in K[S]) (p \cdot r \in \mathcal{I} \text{ and } r \cdot p \in \mathcal{I})$.
3. For each $n \in \mathbb{N}$ let S_n be the group of permutations of $\{1, \dots, n\}$. The group algebra $K[S_n]$ and the two-sided ideals of $K[S_n]$ are defined as above, replacing S by S_n . Identifying permutations of $\{1, \dots, n\}$ with permutations of \mathbb{N} having support included in $\{1, \dots, n\}$, we have $S = \bigcup_{n \in \mathbb{N}} S_n$ and $K[S] = \bigcup_{n \in \mathbb{N}} K[S_n]$.

The next lemma summarizes some known facts from the representation theory of S_n .

Lemma 4.2. RCA_0 proves the following. There is an explicit one-to-one mapping $e : \mathcal{D} \rightarrow K[S]$ with the following properties.

1. The irreducible central idempotents of $K[S_n]$ are $e(D)$, $|D| = n$.
2. Consequently, there is a one-to-one correspondence between two-sided ideals of $K[S_n]$ and sets of diagrams of size n . The two-sided ideal of $K[S_n]$ corresponding to $\mathcal{S} \subseteq \{D \mid |D| = n\}$ is generated by $\{e(D) \mid D \in \mathcal{S}\}$.
3. Let E be a diagram of size $\leq n$. Then $e(E)$ and $\{e(D) \mid |D| = n, E \leq D\}$ generate the same two-sided ideal of $K[S_n]$.

Proof. As noted in [6, Theorem 1], these facts are proved in [13, 4.27, 4.51, 4.52]. Their formalization within RCA_0 is routine. Some other helpful sources are [4, §§23–28] for facts 1 and 2, and [7, Chapter 7] for fact 3. \square

Lemma 4.3. RCA_0 proves the following. There is a one-to-one correspondence between two-sided ideals of $K[S]$ and closed sets of diagrams. The two-sided ideal of $K[S]$ corresponding to a closed set \mathcal{U} of diagrams is generated by $\{e(D) \mid D \in \mathcal{U}\}$. A two-sided ideal of $K[S]$ is finitely generated if and only if the corresponding closed set of diagrams is finitely generated.

Proof. We reason in RCA_0 . Define $\mathcal{T} \subseteq \{E \mid |E| \leq n\}$ to be *n-closed* if

$$\mathcal{T} = \{E \mid |E| \leq n, \forall D ((|D| = n, E \leq D) \Rightarrow D \in \mathcal{S})\}$$

for some $\mathcal{S} \subseteq \{D \mid |D| = n\}$. Lemma 4.2 implies a one-to-one correspondence between n -closed subsets of $\{E \mid |E| \leq n\}$ and two-sided ideals \mathcal{I} of $K[S_n]$, where the n -closed set corresponding to \mathcal{I} is $\{E \mid |E| \leq n, e(E) \in \mathcal{I}\}$. Our lemma then follows upon noting that (1) a set \mathcal{U} of diagrams is closed if and only if $\forall n (\mathcal{U} \cap \{E \mid |E| \leq n\} \text{ is } n\text{-closed})$, and (2) a set $\mathcal{I} \subseteq K[S]$ is a two-sided ideal of $K[S]$ if and only if $\forall n (\mathcal{I} \cap K[S_n] \text{ is a two-sided ideal of } K[S_n])$. \square

We now present the main theorem of this paper.

Theorem 4.4. Over RCA_0 each of the following statements implies the others.

1. $\text{WO}(\omega^\omega)$.
2. There is no infinite ascending sequence of two-sided ideals of $K[S]$.
3. There is no infinite ascending sequence of finitely generated, two-sided ideals of $K[S]$.
4. Every two-sided ideal of $K[S]$ is finitely generated.

Proof. We reason in RCA_0 . The one-to-one correspondence in Lemma 4.3 is such that each two-sided ideal of $K[S]$ is uniformly Δ_1^0 definable from its corresponding closed set of diagrams and vice versa. Therefore, by Δ_1^0 comprehension, the one-to-one correspondence between two-sided ideals $\mathcal{I} \subseteq K[S]$ and closed sets $\mathcal{U} \subseteq \mathcal{D}$ extends to a one-to-one correspondence between sequences $\langle \mathcal{I}_i \rangle_{i \in \mathbb{N}}$ of two-sided ideals of $K[S]$ and sequences $\langle \mathcal{U}_i \rangle_{i \in \mathbb{N}}$ of closed sets of diagrams. We now see that Theorem 4.4 follows from Theorems 2.3 and 3.13. \square

5 Weakening the base theory

The usual base theory for reverse mathematics [26, Part A] is RCA_0 . However, there is an alternative base theory RCA_0^* consisting of RCA_0 with Σ_1^0 induction replaced by exponentiation plus Σ_0^0 induction [26, §IX.4]. Many of the known reversals over RCA_0 can be proved over the weaker base theory RCA_0^* , and in this way one strengthens the reversals [26, Remark X.4.3]. There are also some reversals over RCA_0^* which have no counterpart over RCA_0 , because the theorems in question are provable in RCA_0 and in fact equivalent to RCA_0 over RCA_0^* . The alternative base theory RCA_0^* was introduced and used in [31] and has been used in several subsequent publications including [8, 9, 14, 27, 32, 35].

The purpose of this section is to strengthen some of our reversals in Theorems 2.6 and 3.13 and 4.4 by weakening the base theory from RCA_0 to RCA_0^* . In order to do so, we exercise care in defining the concept “infinite ascending sequence” within RCA_0^* . The following definition of “infinite ascending sequence” is equivalent over RCA_0 to the usual definition with $I = \mathbb{N}$, but the equivalence does not hold over RCA_0^* .

Definition 5.1. Within RCA_0^* we define (a code for) an *infinite sequence of ideals of* $K[S]$ to consist of an infinite set $I \subseteq \mathbb{N}$ together with a set $\mathcal{I} \subseteq K[S] \times I$ such that for each $i \in I$ the set $\mathcal{I}_i = \{p \mid (p, i) \in \mathcal{I}\}$ is an ideal of $K[S]$. Such a sequence is denoted $\langle \mathcal{I}_i \rangle_{i \in I}$. The sequence is said to be *ascending* if $(\forall i \in I) (\forall j \in I) (i < j \Rightarrow \mathcal{I}_i \subsetneq \mathcal{I}_j)$. Similarly within RCA_0^* we define (codes for) infinite (ascending) sequences $\langle \mathcal{U}_i \rangle_{i \in I}$ of (closed or upwardly closed) sets of diagrams.

Lemma 5.2. Over RCA_0^* each of the following statements implies the others.

1. RCA_0 .
2. Σ_1^0 induction.
3. There is no infinite descending sequence in \mathbb{N} . In other words, there is no function $f : I \rightarrow \mathbb{N}$ such that $I \subseteq \mathbb{N}$ is infinite and $(\forall i \in I) (\forall j \in I) (i < j \Rightarrow f(i) > f(j))$.

Proof. We reason in RCA_0^* . For $1 \Leftrightarrow 2$ see [31] or [26, §X.4]. Clearly we have $2 \Rightarrow 3$, so it remains to prove $3 \Rightarrow 2$. Suppose 2 fails. Let $\Phi(m)$ be a Σ_1^0 formula such that $\Phi(1)$ and $\forall m (\Phi(m) \Rightarrow \Phi(m+1))$ and $\exists n \neg \Phi(n)$. Write $\Phi(m) \equiv \exists j \Theta(m, j)$ where $\Theta(m, j)$ is Σ_0^0 . By Σ_0^0 comprehension there is a function $g : \mathbb{N} \rightarrow \{1, \dots, n\}$ defined by $g(i) =$ the least m such that $\neg (\exists j < i) \Theta(m, j)$. Clearly we have $\forall i \forall j (i > j \Rightarrow g(i) \geq g(j))$. By Δ_1^0 comprehension let $I = \{i+1 \mid g(i+1) > g(i)\}$. If the set I were finite, then letting $m_0 + 1 = g(i_0 + 1)$ where $i_0 + 1 =$ the largest element of I , we would have $\Phi(m_0)$ and $\neg \Phi(m_0 + 1)$, a contradiction. Thus I is infinite, so $f : I \rightarrow \mathbb{N}$ defined by $f(i) = n - g(i)$ is an infinite descending sequence, so 3 fails, Q.E.D. \square

Lemma 5.3. Lemmas 4.2 and 4.3 and Theorem 3.8 hold over RCA_0^* .

Proof. The proofs in RCA_0 remain valid in RCA_0^* . The proof of Lemma 4.2 involves Gaussian elimination for finite systems of linear equations over K , but this works perfectly well in RCA_0^* despite the use of Σ_1^0 induction in [26, Exercise II.4.11]. The difference here is that K , unlike the real field \mathbb{R} , is a countable discrete field. \square

The main result of this section is as follows.

Theorem 5.4. Over RCA_0^* each of the following statements implies the others.

1. $\text{RCA}_0 + \text{WO}(\omega^\omega)$.
2. There is no infinite ascending sequence of upwardly closed sets of diagrams.
3. There is no infinite ascending sequence of closed sets of diagrams.
4. There is no infinite ascending sequence of two-sided ideals of $K[S]$.

Proof. We reason in RCA_0^* . By Theorems 2.6 and 3.13 and 4.4, it will suffice to prove that the disjunction $2 \vee 3 \vee 4$ implies RCA_0 . Suppose RCA_0 fails. By Lemma 5.2 there is an infinite descending sequence $f : I \rightarrow \mathbb{N}$. For each $i \in I$ let F_i be the diagram such that $r_1(F_i) = f(i)$ and $r_2(F_i) = 0$. By Lemma 5.3 let \mathcal{I}_i be the two-sided ideal of $K[S]$ corresponding to the closed set $\mathcal{U}_i = \text{cl}(\{F_i\}) = \text{ucl}(\{F_i\})$. Then $\langle \mathcal{U}_i \rangle_{i \in I}$ is an infinite ascending sequence of (upwardly) closed sets of diagrams, and $\langle \mathcal{I}_i \rangle_{i \in I}$ is an infinite ascending sequence of two-sided ideals in $K[S]$. Thus $2 \vee 3 \vee 4$ fails, Q.E.D. \square

In a similar fashion, we can strengthen [24, Theorem 2.7] by weakening the base theory from RCA_0 to RCA_0^* . As in [24] let $K[x_1, \dots, x_n]$ be the ring of polynomials over K in n indeterminates.

Theorem 5.5. Over RCA_0^* each of the following statements implies the other.

1. $\text{RCA}_0 + \text{WO}(\omega^\omega)$.
2. For each $n \in \mathbb{N}$ there is no infinite ascending sequence of ideals in $K[x_1, \dots, x_n]$.

Proof. We reason in RCA_0^* . By [24, Theorem 2.7] we have $1 \Rightarrow 2$. Assume that 2 holds and 1 fails. Then by [24, Theorem 2.7] RCA_0 must fail, so by Lemma 5.2 let $f : I \rightarrow \mathbb{N}$ be an infinite descending sequence. Let $K[x]$ be the ring of polynomials over K in one indeterminate. For each $i \in I$ let \mathcal{I}_i be the ideal in $K[x]$ generated by the monomial x^{m_i} where $m_i = 2^{f(i)}$. Then $\langle \mathcal{I}_i \rangle_{i \in I}$ is an infinite ascending sequence of ideals in $K[x]$, so 2 fails for $n = 1$. This contradiction completes the proof. \square

6 A question for future research

In this section we raise a question for future research.

Maclagen² [15] has shown that monomial ideals in the polynomial ring $K[x_1, \dots, x_n]$ satisfy the *antichain condition*, i.e., there is no infinite sequence of such ideals which are pairwise incomparable under inclusion. Maclagen's argument also gives the same result for the power series ring $K[[x_1, \dots, x_n]]$. And in a similar vein we have the following result, which is apparently new.

Theorem 6.1. Let $K[S]$ be as in §4. Then, the two-sided ideals in $K[S]$ satisfy the antichain condition. In other words, there is no infinite sequence of two-sided ideals in $K[S]$ which are pairwise incomparable under inclusion.

Proof. The *better partial orderings* [17] are a subclass of the well partial orderings. Many of the well partial orderings which arise in practice are actually better partial orderings. However, the class of better partial orderings enjoys many infinitary closure properties which are not shared by the class of well partial orderings. A key result of this kind due to Nash-Williams³ [17] implies the following:

(1)

If \mathcal{P} is a better partial ordering, then the downwardly closed subsets of \mathcal{P} form a better partial ordering under inclusion.

Taking complements, we also have:

(2)

If \mathcal{P} is a better partial ordering, then the upwardly closed subsets of \mathcal{P} form a better partial ordering under reverse inclusion.

Applying (1) to the better partial ordering \mathbb{N}^n , we see that \mathcal{D}_n (see Remark 3.14) is a better partial ordering. And then, applying (2) to \mathcal{D}_n , we see that the upwardly closed subsets of \mathcal{D}_n are better partially ordered under reverse inclusion. Letting $n = 2$, it follows by Lemma 4.3 that the two-sided ideals of $K[S]$ are better partially ordered under reverse inclusion, so in particular they satisfy the antichain condition. \square

Remark 6.2. The calculations of Aschenbrenner and Pong [2] can be used to show that Maclagen's result is reverse-mathematically equivalent to $\text{WO}(\omega^{\omega^\omega})$. It is also known [24, Theorem 2.9] that the Robson Basis Theorem [19, Theorem 3.15] is reverse-mathematically equivalent to $\text{WO}(\omega^{\omega^\omega})$, and we conjecture that $\forall n \text{ WPO}(\mathcal{D}_n)$ has the same reverse-mathematical status. In view of Theorem 4.4, it would be interesting to determine the reverse-mathematical status of Theorem 6.1.

References

- [1] George E. Andrews. *The Theory of Partitions*. Cambridge University Press, 2014. XVI + 273 pages. 3, 6, 8
- [2] Matthias Aschenbrenner and Wai Yan Pong. Orderings of monomial ideals. *Fundamenta Mathematicae*, 181(1):27–74, 2004. 12

²We thank Florian Pelupessy for calling our attention to [2, 15].

³See also our exposition in [22].

- [3] C.-T. Chong, Q. Feng, T. A. Slaman, and W. H. Woodin, editors. *Infinity and Truth*. Number 25 in IMS Lecture Notes Series, Institute for Mathematical Sciences, National University of Singapore. World Scientific, 2014. IX + 234 pages. [14](#)
- [4] Charles W. Curtis and Irving Reiner. *Representation Theory of Finite Groups and Associative Algebras*. Interscience, John Wiley and Sons, 1962. XIV + 689 pages. [3](#), [6](#), [9](#)
- [5] D. H. J. de Jongh and Rohit Parikh. Well-partial orderings and hierarchies. *Indagationes Mathematicae*, 80(3):195–207, 1977. [4](#)
- [6] Edward Formanek and John Lawrence. The group algebra of the infinite symmetric group. *Israel Journal of Mathematics*, 23(3–4):325–331, 1976. [3](#), [6](#), [9](#)
- [7] William Fulton. *Young Tableaux With Applications to Representation Theory and Geometry*. Number 35 in London Mathematical Society Student Texts. Cambridge University Press, 1997. IX + 260 pages. [6](#), [9](#)
- [8] Kostas Hatzikiriakou. Algebraic disguises of Σ_1^0 induction. *Archive for Mathematical Logic*, 29(1):47–51, 1989. [10](#)
- [9] Kostas Hatzikiriakou. *Commutative Algebra in Subsystems of Second Order Arithmetic*. PhD thesis, Pennsylvania State University, 1989. VII + 43 pages. [10](#)
- [10] Kostas Hatzikiriakou. A note on ordinal numbers and rings of formal power series. *Archive for Mathematical Logic*, 33(4):261–263, 1994. [2](#)
- [11] David Hilbert. Ueber die Theorie der algebraischen Formen. *Mathematische Annalen*, 36(4):473–534, 1890. <http://dx.doi.org/10.1007/BF01208503>. [2](#)
- [12] David Hilbert. Über das Unendliche. *Mathematische Annalen*, 95(1):161–190, 1926. [2](#)
- [13] Adalbert Kerber. *Representations of Permutation Groups I*. Number 240 in Lecture Notes in Mathematics. Springer-Verlag, 1971. V + 192 pages. [9](#)
- [14] Leszek Aleksander Kołodziejczyk and Keita Yokoyama. Categorical characterizations of the natural numbers require primitive recursion. *Annals of Pure and Applied Logic*, 166(2):219–231, 2015. [10](#)
- [15] Diane Maclagen. Antichains of monomial ideals are finite. *Proceedings of the American Mathematical Society*, 129(6):1609–1615, 2000. [12](#)
- [16] Richard Mansfield and Galen Weitkamp. *Recursive Aspects of Descriptive Set Theory*. Oxford Logic Guides. Oxford University Press, 1985. VI + 144 pages. [14](#)
- [17] Crispin St. J. A. Nash-Williams. On better-quasi-ordering transfinite sequences. *Mathematical Proceedings of the Cambridge Philosophical Society*, 64(2):273–290, 1968. [12](#)
- [18] Max Noether. Paul Gordan. *Mathematische Annalen*, 75(1):1–41, 1914. [2](#)
- [19] J. C. Robson. Well quasi-ordered sets and ideals in free semigroups and algebras. *Journal of Algebra*, 55(2):521–535, 1978. [12](#)
- [20] Diana Schmidt. *Well-Partial Orderings and Their Maximal Order Types*. Habilitationsschrift, University of Heidelberg, 1979, IV + 77 pages. [4](#)
- [21] S. G. Simpson, editor. *Logic and Combinatorics*. Contemporary Mathematics. American Mathematical Society, 1987. XI + 394 pages. [14](#)

- [22] Stephen G. Simpson. BQO theory and Fraïssé’s conjecture. In [16], pages 124–138, 1985. [4](#), [12](#)
- [23] Stephen G. Simpson. Nichtbeweisbarkeit von gewissen kombinatorischen Eigenschaften endlicher Bäume. *Archiv für mathematische Logik und Grundlagenforschung*, 25(1):45–65, 1985. [4](#)
- [24] Stephen G. Simpson. Ordinal numbers and the Hilbert basis theorem. *Journal of Symbolic Logic*, 53(3):961–974, 1988. [2](#), [3](#), [4](#), [11](#), [12](#)
- [25] Stephen G. Simpson. Partial realizations of Hilbert’s program. *Journal of Symbolic Logic*, 53(2):349–363, 1988. [2](#)
- [26] Stephen G. Simpson. *Subsystems of Second Order Arithmetic*. Perspectives in Mathematical Logic. Springer-Verlag, 1999. XIV + 445 pages; Second Edition, Perspectives in Logic, Association for Symbolic Logic, Cambridge University Press, 2009, XVI + 444 pages. [2](#), [5](#), [7](#), [8](#), [10](#), [11](#)
- [27] Stephen G. Simpson. Baire categoricity and Σ_1^0 induction. *Notre Dame Journal of Formal Logic*, 55(1):75–78, 2014. [10](#)
- [28] Stephen G. Simpson. An objective justification for actual infinity? In [3], pages 225–228, 2014. [2](#)
- [29] Stephen G. Simpson. Toward objectivity in mathematics. In [3], pages 157–169, 2014. [2](#)
- [30] Stephen G. Simpson. Comparing $\text{WO}(\omega^\omega)$ with Σ_2^0 induction. [arXiv:1508.02655](#), 11 August 2015. 6 pages. [2](#)
- [31] Stephen G. Simpson and Rick L. Smith. Factorization of polynomials and Σ_1^0 induction. *Annals of Pure and Applied Logic*, 31:289–306, 1986. [10](#), [11](#)
- [32] Stephen G. Simpson and Keita Yokoyama. Reverse mathematics and Peano categoricity. *Annals of Pure and Applied Logic*, 164(3):284–293, 2013. [10](#)
- [33] William W. Tait. Finitism. *Journal of Philosophy*, 78(9):524–546, 1981. [2](#)
- [34] Fons van Engelen, Arnold W. Miller, and John Steel. Rigid Borel sets and better quasi-order theory. In [21], pages 199–222, 1987. [4](#)
- [35] Keita Yokoyama. On the strength of Ramsey’s Theorem without Σ_1 -induction. *Mathematical Logic Quarterly*, 59(1–2):108–111, 2013. [10](#)