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More reverse mathematics of the Heine-Borel theorem

a joint research project of
Jeff Hirst and Jessica Miller¹
Department of Mathematical Sciences
Appalachian State University

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October 21, 2011

¹ Jessica's research was supported by a two semester research assistantship from the **Graduate Research Associate Mentoring** program of the Cratis D. Williams Graduate School.

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- MR1133006 (92m:03093)** Friedman, Harvey M.; Hirst, Jeffrey L. Reverse mathematics and homeomorphic embeddings. *Ann. Pure Appl. Logic* 54 (1991), no. 3, 229–253. (Reviewer: Mariko Yasugi), 03F35
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Let ATR_0 be the subsystem of second order arithmetic consisting of ACA_0 (the basic ordered semiring axioms and the induction scheme for Σ_1^1 formulas as well as the induction axiom and the arithmetical comprehension scheme) plus all instances of: $\forall X(WO(X) \rightarrow \exists YH_\theta(X, Y))$ where θ is arithmetical (and where $WO(X) \equiv: X$ is a well ordering and $H_\theta(X, Y)$ says that Y is the result of iterating the arithmetical formula θ along the ordering X). Define two countable well orderings to be (1) weakly comparable if there is an order-preserving injection of one into the other and (2) strongly comparable if the injection is an isomorphism between one ordering and an initial segment of the other. The aim of the paper under review is to give detailed proofs of the following two results: (a) The statement "any two countable well orderings are strongly comparable" is equivalent to ATR_0 (announced by Friedman and proved by S. Simpson), and (b) the statement "any two countable well orderings are weakly comparable" is equivalent to ATR_0 (Friedman).

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Annals of Pure and Applied Logic 47 (1990) 11-29
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WEAK COMPARABILITY OF WELL ORDERINGS AND REVERSE MATHEMATICS

Harvey M. FRIEDMAN and Jeffrey L. HIRST
Department of Mathematics, The Ohio State University, 231 West 18th Avenue, Columbus, OH
43210-1174, USA

Communicated by A. Nerode
Received 26 January 1989

Two countable well orderings are weakly comparable if there is an order preserving injection of one into the other. We say the well orderings are strongly comparable if the injection is an isomorphism between one ordering and an initial segment of the other. In [5], Friedman announced that the statement "any two countable well orderings are strongly comparable" is equivalent to ATR_0 . Simpson provides a detailed proof of this result in Chapter 5 of [13]. More recently, Friedman has proved that the statement "any two countable well orderings are weakly comparable" is equivalent to ATR_0 . The main goal of this paper is to give a detailed exposition of this result.

1. Reverse mathematics

This paper analyzes the provability of certain statements within weak subsystems of second order arithmetic. The framework of axioms used here consists

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and order arithmetic consisting of ACA_0 (the basic ordered semiring axioms) plus the induction axiom and the arithmetical comprehension $WO(X) \rightarrow \exists Y \theta(X, Y)$ where θ is arithmetical (and where $WO(X) \equiv X$ is a well ordering of X). The result of iterating the arithmetical formula θ along the ordering X is θ^X . The statement (1) "any two countable well orderings are weakly comparable" is equivalent to ATR_0 if and only if the injection is an isomorphism between one ordering and an initial segment of the other. The main goal of the paper under review is to give detailed proofs of the following two theorems: (a) "any two countable well orderings are strongly comparable" is equivalent to ATR_0 (proved by S. Simpson), and (b) the statement "any two countable well orderings are weakly comparable" is equivalent to ATR_0 (Friedman).

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257 \it Proof of the claim:}
258 To prove the reverse implication, suppose that for every  $\sigma$ , if
259  $x \in \overline{A_\sigma}$  then  $x \in \overline{A_{\sigma \cap 0}}$ 
260 or  $x \in \overline{A_{\sigma \cap 1}}$ . Thus we have a sequence of rapidly shrinking neighborhoods
261  $A_{\sigma_i}$ , each of
262 which contain  $x$ . The associated sequence of distinct reals  $\langle x_{\sigma_i} \rangle$ 
263 converges to  $x$ .
264
265 To prove the forward implication, we will prove the contrapositive. Suppose
266 there is a  $\sigma$  such that  $x \in \overline{A_\sigma}$  but  $x \notin \overline{A_{\sigma \cap 0}} \cup \overline{A_{\sigma \cap 1}}$ .
267 Either  $x = x_\sigma$  or  $x \neq x_\sigma$ . Then either  $A_\sigma \setminus \overline{A_{\sigma \cap 0}} \cup \overline{A_{\sigma \cap 1}}$ 
268 or  $\overline{A_\sigma} \setminus \overline{A_{\sigma \cap 0}} \cup \overline{A_{\sigma \cap 1}}$ , respectively, is an open set containing  $x$  and
269 no other element of  $\mathbb{R} \setminus \{x_\sigma\}$ . So  $x$  is not an
270 accumulation point of  $\mathbb{R} \setminus \{x_\sigma\}$ ,
271 completing the proof of the claim.
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Jeffrey L Hirst and Jessica Miller

Claim Let $x \in [0, 1]$. The real x is an accumulation point of $\{x_\sigma \mid \sigma \in 2^{\mathbb{N}}\}$ if and only if for every σ , if $x \in \overline{A}_\sigma$ then $x \in \overline{A}_{\sigma \cdot 0}$ or $x \in \overline{A}_{\sigma \cdot 1}$.

Proof of the claim: To prove the reverse implication, suppose that for every σ , if $x \in \overline{A}_\sigma$ then $x \in \overline{A}_{\sigma \cdot 0}$ or $x \in \overline{A}_{\sigma \cdot 1}$. Thus we have a sequence of rapidly shrinking neighborhoods A_{σ_i} , each of which contain x . The associated sequence of distinct reals $\{x_{\sigma_i}\}_{i \in \mathbb{N}}$ converges to x .

To prove the forward implication, we will prove the contrapositive. Suppose there is a σ such that $x \in \overline{A}_\sigma$ but $x \notin (\overline{A}_{\sigma \cdot 0} \cup \overline{A}_{\sigma \cdot 1})$. Either $x = x_\sigma$ or $x \neq x_\sigma$. Then either $A_\sigma - (\overline{A}_{\sigma \cdot 0} \cup \overline{A}_{\sigma \cdot 1})$ or $P_\sigma - (\overline{A}_{\sigma \cdot 0} \cup \overline{A}_{\sigma \cdot 1})$, respectively, is an open set containing x and no other element of $\{x_\sigma \mid \sigma \in 2^{\mathbb{N}}\}$. So x is not an accumulation point of $\{x_\sigma \mid \sigma \in 2^{\mathbb{N}}\}$, completing the proof of the claim.

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W. A. Mozart
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D. Taupin

Flûte

Hautbois
Violon

Orgue

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More reverse mathematics of the Heine-Borel Theorem

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current formulations seem to have some applicability. For example, Hirst's [4] result showing that the Heine-Borel Theorem for $\mathbb{Q} \cap [0, 1]$ implies WKL_0 is an immediate consequence of Theorem 2. Also, Friedman and Hirst [3] define a canonical embedding of a well ordered set into $[0, 1]$. Working in RCA_0 , if we can show that $X \subseteq [0, 1]$ is a countable closed set and is the range of this sort of canonical embedding of a well ordering, then Theorem 1 shows that the Heine-Borel Theorem holds for X .

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- [2] **HM Friedman**, *Systems of second order arithmetic with restricted induction, I, II (abstracts)*, J. Symbolic Logic 41 (1976) 557–559
- [3] **HM Friedman, JL Hirst**, *Reverse mathematics and homeomorphic embeddings*, Ann. Pure Appl. Logic 54 (1991) 229–253
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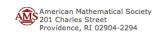
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Let ATR_0 be the subsystem of second order arithmetic consisting of ACA_0 (the basic ordered semiring axioms and the induction scheme for Σ_1^1 formulas as well as the induction axiom and the arithmetical comprehension scheme) plus all instances of: $\forall X(WO(X) \rightarrow \exists YH_\theta(X, Y))$ where θ is arithmetical (and where $WO(X) := X$ is a well ordering and $H_\theta(X, Y)$ says that Y is the result of iterating the arithmetical formula θ along the ordering X). Define two countable well orderings to be (1) weakly comparable if there is an order-preserving injection of one into the other and (2) strongly comparable if the injection is an isomorphism between one ordering and an initial segment of the other. The aim of the paper under review is to give detailed proofs of the following two results: (a) The statement "any two countable well orderings are strongly comparable" is equivalent to ATR_0 (announced by Friedman and proved by S. Simpson), and (b) the statement "any two countable well orderings are weakly comparable" is equivalent to ATR_0 (Friedman).

- [1]
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Reviewed by Roman Murawski

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\bib{MR1050559}{article}{
author={Friedman, Harvey M.},
author={Hirst, Jeffrey L.},
title={Weak comparability of well orderings and reverse mathematics},
journal={Ann. Pure Appl. Logic},
volume={47},
date={1990},
number={1},
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