

Muchnik and Medvedev
Degrees of Π_1^0 Subsets of 2^ω

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AMS Special Session
Columbus, Ohio
September 21–23, 2001

Outline of talk:

1. The Gödel Hierarchy.
2. Reverse Mathematics and WKL_0 .
3. Forcing with Π_1^0 subsets of 2^ω .
4. A symmetric ω -model of WKL_0 .
5. A symmetric β -model.
6. Muchnik and Medvedev degrees of Π_1^0 sets.
7. Structural (lattice-theoretic) results.
8. Some classes of Muchnik degrees.
9. Some specific Muchnik and Medvedev degrees (an invidious comparison).
10. References.

The Gödel Hierarchy:

strong {

- ∴
- supercompact cardinal
- ∴
- measurable cardinal
- ∴
- ZFC (ZF set theory with choice)
- Zermelo set theory
- simple type theory

medium {

- Z_2 (2nd order arithmetic)
- ∴
- Π_2^1 comprehension
- Π_1^1 comprehension
- ATR_0 (arith. transfinite recursion)
- ACA_0 (arithmetical comprehension)

weak {

- WKL_0 (weak König's lemma)
- RCA_0 (recursive comprehension)
- PRA (primitive recursive arithmetic)
- EFA (elementary arithmetic)
- bounded arithmetic
- ∴

Reverse Mathematics:

Let τ be a mathematical theorem. Let S_τ be the weakest natural subsystem of second order arithmetic in which τ is provable.

1. Very often, the principal axiom of S_τ is logically equivalent to τ .
2. Furthermore, only a few subsystems of second order arithmetic arise in this way.

This classification program provides an interesting picture of the logical structure of contemporary mathematics.

It is a contribution to foundations of mathematics (f.o.m.).

Books on Reverse Mathematics:

1.

Stephen G. Simpson

Subsystems of Second Order Arithmetic

Perspectives in Mathematical Logic

Springer-Verlag, 1999

XIV + 445 pages

<http://www.math.psu.edu/simpson/sosoa/>

2.

S. G. Simpson (editor)

Reverse Mathematics 2001

A volume of papers by various authors,
to appear in 2001,
approximately 400 pages.

<http://www.math.psu.edu/simpson/revmath/>

An important system:

One of the most important systems for Reverse Mathematics is WKL_0 .

WKL_0 is a subsystem of second order arithmetic.

WKL_0 includes Δ_1^0 comprehension (i.e., closure under Turing reducibility) and Weak König's Lemma: (i.e., every infinite subtree of the full binary tree has an infinite path).

Remarks on ω -models of WKL_0 :

1. The ω -model

$$\text{REC} = \{X \subseteq \omega : X \text{ is recursive}\}$$

is not an ω -model of WKL_0 . (Kleene)

2. However, REC is the intersection of all ω -models of WKL_0 . (Kreisel, "hard core")

Remarks on ω -models of WKL_0 (continued):

3. The ω -models of WKL_0 are just the *Scott systems*, i.e., $M \subseteq P(\omega)$ such that

(a) $M \neq \emptyset$.

(b) $X, Y \in M$ implies $X \oplus Y \in M$.

(c) $X \in M, Y \leq_T X$ imply $Y \in M$.

(d) If $T \in M$ is an infinite subtree of $2^{<\omega}$, then there exists $X \in M$ such that X is a path through T .

Dana Scott, Algebras of sets binumerable in complete extensions of arithmetic, *Recursive Function Theory*, AMS, 1962, pages 117–121.

Remarks on ω -models of WKL_0 (continued):

4. There is a close relationship between

(a) ω -models of WKL_0 , and

(b) Π_1^0 subsets of 2^ω .

The recursion-theoretic literature is extensive, with numerous articles by Jockusch, Kučera, and others. A recent survey is:

Douglas Cenzer and Jeffrey B. Remmel, Π_1^0 classes in mathematics, *Handbook of Recursive Mathematics*, North-Holland, 1998, pages 623–821.

An interesting ω -model of WKL_0 :

Let \mathcal{P} be the nonempty Π_1^0 subsets of 2^ω , ordered by inclusion. Forcing with \mathcal{P} is known as Jockusch/Soare forcing.

Lemma (Simpson 2000). Let X be J/S generic. Suppose $Y \leq_T X$. Then (i) Y is J/S generic, and (ii) X is J/S generic relative to Y .

Theorem (Simpson 2000). There is an ω -model M of WKL_0 with the following property: For all $X, Y \in M$, X is definable from Y in M if and only if X is Turing reducible to Y .

Proof. M is obtained by iterated J/S forcing. We have

$$M = \text{REC}[X_1, X_2, \dots, X_n, \dots]$$

where, for all n , X_{n+1} is J/S generic over $\text{REC}[X_1, \dots, X_n]$. To show that M has the desired property, we use symmetry arguments based on the Recursion Theorem.

Foundational significance of M :

The above ω -model, M , represents a compromise between the conflicting needs of

(a) recursive mathematics (“everything is computable”)

and

(b) classical rigorous mathematics as developed in WKL_0 (“every continuous real-valued function on $[0, 1]$ attains a maximum”, “every countable commutative ring has a prime ideal”, etc etc).

Namely, M contains enough nonrecursive objects for WKL_0 to hold, yet the recursive objects form the “definable core” of M .

Foundational significance (continued):

More generally, consider the scheme

(*) For all X and Y , if X is definable from Y then X is recursive in Y

in the language of second order arithmetic.

Often in mathematics, under some assumptions on a given countably coded object X , there exists a unique countably coded object Y having some property stated in terms of X . In this situation, (*) implies that Y is Turing computable from X . This is of obvious f.o.m. significance.

Simpson 2000 shows that, for every countable model of WKL_0 , there exists a countable model of $WKL_0 + (*)$ with the same first order part.

Thus $WKL_0 + (*)$ is conservative over WKL_0 for first order arithmetical sentences.

Earlier results of Friedman:

In an unpublished 1974 manuscript, Friedman obtained (by a different method) an ω -model M of WKL_0 with the following property: For all $X \in M$, X is definable in M if and only if X is recursive.

In the same 1974 manuscript, Friedman proved another result which stands in contradiction to my theorem above, concerning relative definability and relative recursiveness. Friedman's proof of this other result is erroneous.

A Π_1^0 set of ω -models of WKL_0 :

Theorem (Simpson 2000). There is a nonempty Π_1^0 subset of 2^ω , P , such that:

1. For all $X \in P$, $\{(X)_n : n \in \omega\}$ is a countable ω -model of WKL_0 , and every countable ω -model of WKL_0 occurs in this way.
2. For all nonempty Π_1^0 sets $P_1, P_2 \subseteq P$ we can find a recursive homeomorphism

$$F : P_1 \cong P_2$$

such that for all $X \in P_1$ and $Y \in P_2$, if $F(X) = Y$ then

$$\{(X)_n : n \in \omega\} = \{(Y)_n : n \in \omega\} .$$

The proof uses an idea of Pour-El/Kripke 1967.

Hyperarithmetical analogs:

Theorem (Simpson 2000). There is a countable β -model M such that, for all $X, Y \in M$, X is definable from Y in M if and only if X is hyperarithmetical in Y .

In the language of second order arithmetic, consider the scheme

(**) for all X, Y , if X is definable from Y , then X is hyperarithmetical in Y .

Theorem (Simpson 2000).

1. $\text{ATR}_0 + (**)$ is conservative over ATR_0 for Σ_2^1 sentences.
2. $\Pi_\infty^1\text{-TI}_0 + (**)$ is conservative over $\Pi_\infty^1\text{-TI}_0$ for Σ_2^1 sentences.

Two new structures in recursion theory:

Recall that \mathcal{P} is the set of nonempty Π_1^0 subsets of 2^ω .

\mathcal{P}_w (\mathcal{P}_M) consists of the Muchnik (Medvedev) degrees of members of \mathcal{P} , ordered by Muchnik (Medvedev) reducibility.

P is Muchnik reducible to Q ($P \leq_w Q$) if for all $Y \in Q$ there exists $X \in P$ such that $X \leq_T Y$.

P is Medvedev reducible to Q ($P \leq_M Q$) if there exists a recursive functional $F : Q \rightarrow P$.

Note: \leq_M is a uniform version of \leq_w .

\mathcal{P}_w and \mathcal{P}_M are countable distributive lattices with 0 and 1.

The lattice operations are given by

$$P \times Q = \{X \oplus Y : X \in P, Y \in Q\}$$

(least upper bound)

$$P + Q = \{\langle 0 \rangle \frown X : X \in P\} \cup \{\langle 1 \rangle \frown Y : Y \in Q\}$$

(greatest lower bound).

$P \equiv 0$ in \mathcal{P}_w if and only if $P \cap \text{REC} \neq \emptyset$.

$P \equiv 0$ in \mathcal{P}_M if and only if $P \cap \text{REC} \neq \emptyset$.

$P \equiv 1$ in \mathcal{P}_w , i.e., P is *Muchnik complete*, if and only if the Turing degrees of members of P are exactly the Turing degrees of complete extensions of PA. (Simpson 2001)

$P \equiv 1$ in \mathcal{P}_M , i.e., P is *Medvedev complete*, if and only if P is recursively homeomorphic to the set of complete extensions of PA. (Simpson 2000)

Connection with Lindenbaum algebras:

Stone duality gives a 1-1 correspondence

$$P \longleftrightarrow B_P$$

between *members of \mathcal{P}* (i.e., nonempty Π_1^0 subsets of 2^ω) and *Lindenbaum sentence algebras of r.e. theories* (i.e., Boolean algebras of the form B/I , where B is the countable free Boolean algebra, and I is an r.e. ideal in B).

Moreover, this correspondence is *functorial*.

Namely, recursive functionals $F : Q \rightarrow P$ (i.e., Medvedev reductions) correspond to recursive homomorphisms $B_F : B_P \rightarrow B_Q$.

This provides an alternative way to view Medvedev reducibility: $P \leq_M Q$ if and only if there exists a recursive homomorphism $h : B_P \rightarrow B_Q$.

Structural (lattice-theoretic) results:

Trivially $P, Q > 0$ implies $P + Q > 0$, but we do not know whether $P, Q < 1$ implies $P \times Q < 1$.

In \mathcal{P}_ω , for every $P > 0$, every countable distributive lattice is lattice embeddable below P . For \mathcal{P}_M we have partial results in this direction.

To construct our lattice embeddings, we use infinitary “almost lattice” operations, defined in such a way that, if $\langle P_i : i \in \omega \rangle$ is a recursive sequence of members of \mathcal{P} , then

$$\prod_{i=0}^{\infty} P_i \quad \text{and} \quad \sum_{i=0}^{\infty} P_i$$

are again members of \mathcal{P} . We also use a finite injury priority argument a la Martin/Pour-El 1970 and Jockusch/Soare 1972. To push the embeddings below P , we use a Sacks preservation strategy.

This is ongoing joint work with my Ph. D. student Stephen Binns.

Structural results (continued):

Corollary. In \mathcal{P}_w , for all $P >_w 0$ there exists Q such that $P >_w Q >_w 0$.

(nonexistence of minimal Muchnik degrees)

Corollary. In \mathcal{P}_M , for all $P >_M 0$ there exists Q such that $P >_M Q >_M 0$.

(nonexistence of minimal Medvedev degrees)

The last corollary was also obtained by Douglas Cenzer and Peter Hinman, using a different method: index sets.

Problem area:

Study structural properties of the countable distributive lattices \mathcal{P}_w and \mathcal{P}_M . Lattice embeddings, extensions of embeddings, quotient lattices, cupping and capping, automorphisms, definability, decidability, etc.

Some new results:

Theorem (Simpson/Slaman, 2001). Each nonzero Muchnik degree in \mathcal{P}_w contains infinitely many Medvedev degrees. In fact, for each $P >_M 0$ there exists $Q \equiv_w P$ such that $P >_M Q >_M 0$.

Theorem (Cenzer/Hinman, 2001). The partial ordering of Medvedev degrees, \mathcal{P}_M , is dense.

Preprint, 18 pages, August 2001.

The density theorem for the Muchnik degrees, \mathcal{P}_w , remains open. Also, the splitting theorem, for both the Medvedev degrees and the Muchnik degrees, remains open.

Another problem area:

One may study properties of interesting subsets of \mathcal{P}_w and \mathcal{P}_M . For example, we may consider Muchnik and Medvedev degrees of $P \in \mathcal{P}$ with the following special properties:

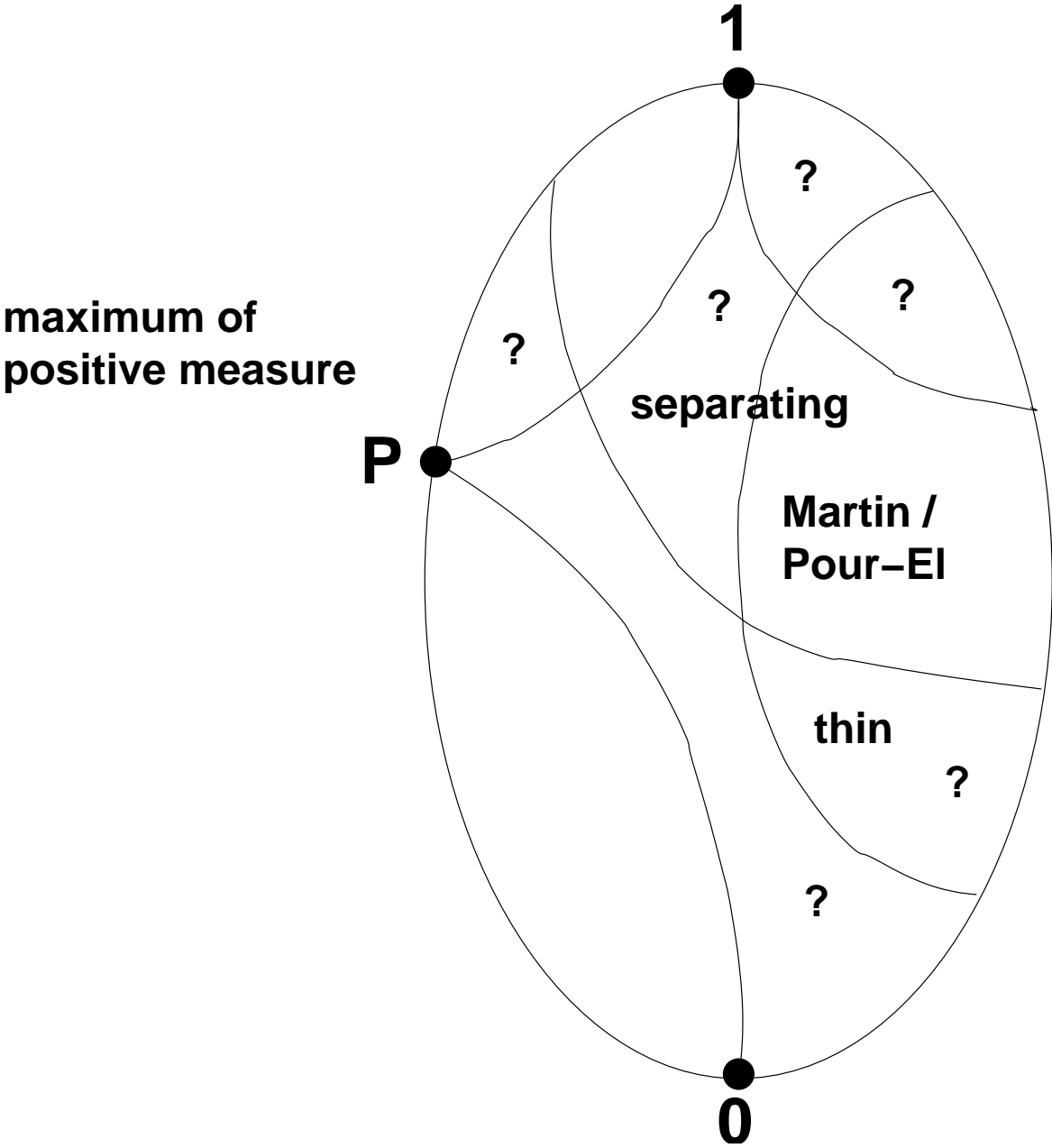
1. P is of positive measure.
2. P is *thin*, i.e., for all Π_1^0 sets $Q \subseteq P$ there exists a clopen set $U \subseteq 2^\omega$ such that $P \cap U = Q$. (See also the recent paper of Cholak/Coles/Downey/Herrmann.)
3. P is *separating*, i.e.,

$$P = \{X \in 2^\omega : X \text{ separates } A, B\}$$

where A, B is a disjoint pair of r.e. sets.

These classes of Medvedev and Muchnik degrees are related in interesting ways.

A picture of the Muchnik lattice \mathcal{P}_w :



An invidious comparison:

In some ways, the study of \mathcal{P}_w and \mathcal{P}_M parallels the study of \mathcal{R}_T , the Turing degrees of recursively enumerable subsets of ω .

Analogy:
$$\frac{\mathcal{P}_w}{\mathcal{R}_T} = \frac{\text{WKL}_0}{\text{ACA}_0}$$

A regrettable aspect of \mathcal{R}_T is that there are **no specific known examples** of recursively enumerable Turing degrees $\neq 0, 0'$. (See the extensive FOM discussion of July 1999, in the aftermath of the Boulder meeting.)

In this respect, \mathcal{P}_w and \mathcal{P}_M are **much better**.

Invidious comparison (continued):

For example, we have:

Theorem (Simpson 1999). The set of Muchnik degrees of Π_1^0 subsets of 2^ω of positive measure contains a maximum degree. Call it \mathbf{r}_1 .

Note that $0 < \mathbf{r}_1 < 1$ in \mathcal{P}_w . Thus \mathbf{r}_1 is a “naturally occurring” intermediate degree!

The theorem follows from three known results.

1. $\{X : X \text{ is 1-random}\}$ is Σ_2^0 and of measure one. (Martin-Löf 1966)
2. $\{X : \exists Y \leq_T X \text{ (} Y \text{ separates a recursively inseparable pair of r.e. sets)}\}$ is of measure zero. (Jockusch/Soare 1972)
3. If $P \in \mathcal{P}$ is of positive measure, then for all 1-random X there exists k such that $X^{(k)} = \lambda n.X(n+k) \in P$. (Kučera 1985)

Additional properties of r_1 :

Theorem (Simpson 2001). The Muchnik degree r_1 does not join to 1. I.e., there does not exist $p < 1$ in \mathcal{P}_w such that $p \times r_1 = 1$.

Theorem (Simpson 2001). The Muchnik degree r_1 is meet-irreducible in \mathcal{P}_w . I.e., there do not exist $p, q > r_1$ in \mathcal{P}_w such that $r_1 = p + q$.

Theorem (Simpson 2001). Let q be the Muchnik degree of a thin Π_1^0 set. If $q > 0$, then q is incomparable with r_1 .

A lemma used in proving these theorems:

Lemma. If $P, Q \in \mathcal{P}$ and $P \leq_w Q$, then there exists $R \subseteq Q$, $R \in \mathcal{P}$, such that $P \leq_M R$.

Foundational significance:

All of these results are informative with respect to ω -models of $WWKL_0$. $WWKL_0$ is a subsystem of second order arithmetic which arises in the Reverse Mathematics of measure theory. (Yu/Simpson 1990)

What about Medvedev degrees?

Theorem (Simpson/Slaman, 2001). There is no maximum Medvedev degree of Π_1^0 subsets of 2^ω of positive measure.

In fact, for all $P \in \mathcal{P}$ of positive measure, there exists $P^* \in \mathcal{P}$ of positive measure, such that $P^* >_M P$.

S. Simpson and T. Slaman, Medvedev degrees of Π_1^0 subsets of 2^ω , to appear.

Some specific Medvedev degrees $\neq 0, 1$:

For $k \geq 2$ let DNR_k be the set of k -valued DNR functions. Each DNR_k is recursively homeomorphic to a member of \mathcal{P} . DNR_2 is Medvedev complete. In \mathcal{P}_M we have

$$\text{DNR}_2 >_M \text{DNR}_3 >_M \cdots >_M \sum_{k=2}^{\infty} \text{DNR}_k .$$

All of these Medvedev degrees are Muchnik complete. (Jockusch 1989)

Problem area:

Find additional natural examples of Medvedev and Muchnik degrees $\neq 0, 1$.

Experience suggests that natural examples could be of significance for f.o.m.

A related problem of Reverse Mathematics:

Let $\text{DNR}(k)$ be the statement that for all X there exists a k -valued DNR function relative to X . It is known that, for each $k \geq 2$, $\text{DNR}(k)$ is equivalent to Weak König's Lemma over RCA_0 . Is $\exists k (k \geq 2 \wedge \text{DNR}(k))$ equivalent to Weak König's Lemma over RCA_0 ?

This has a bearing on graph coloring problems in Reverse Mathematics. See two recent papers of James H. Schmerl, to appear in *MLQ* and *Reverse Mathematics 2001*.

References:

Stephen G. Simpson, Kazuyuki Tanaka, and Takeshi Yamazaki, Some conservation results on weak König's lemma, preprint, February 2000, 26 pages, to appear in APAL.

Stephen G. Simpson, Π_1^0 sets and models of WKL_0 , preprint, April 2000, 28 pages, to appear in *Reverse Mathematics 2001*.

Stephen G. Simpson, A symmetric β -model, preprint, May 2000, 7 pages, to appear.

Stephen Binns and Stephen G. Simpson, Medvedev and Muchnik degrees of Π_1^0 subsets of 2^ω , in preparation.

Stephen G. Simpson, Some Muchnik degrees of Π_1^0 subsets of 2^ω , in preparation.

Some of my papers are available at
<http://www.math.psu.edu/simpson/papers/>.

Transparencies for my talks are available at
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THE END