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## **DEGREES OF MEMBERS OF $\Pi_1^0$ CLASSES**

CARL GROOS JOCKUSCH, JR. AND ROBERT IRVING SOARE

## DEGREES OF MEMBERS OF $\Pi_1^0$ CLASSES

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This paper deals with the degrees of members of  $\Pi_1^0$  classes of sets or function which lack recursive members. For instance, it is shown that if  $\alpha$  is a degree and  $0 < \alpha \leq 0'$ , then there exists a  $\Pi_1^0$  class of sets which has a member of degree  $\alpha$  but none of degree 0. By way of contrast there is no  $\Pi_1^0$  class of functions which has members of all nonzero r.e. degrees but no recursive members. Furthermore, each nonempty  $\Pi_1^0$  class of sets has a member of r.e. degree but not necessarily of r.e. degree less than  $0'$ . As corollaries results are derived about degrees of theories and degrees of models such as: (1) There is an axiomatizable, essentially undecidable theory with a complete extension of minimal degree; (2) (Scott-Tennenbaum): There is a complete extension of Peano arithmetic of degree  $0'$  but none of r.e. degree  $< 0'$ ; (3) There is no nonstandard model of Peano arithmetic of r.e. degree  $< 0'$ . The recursion theorem is applied to yield new information about standard constructions such as Yates' simple non-hypersimple set of given nonzero r.e. degree.

We now turn to definitions and notation. Let  $N$  be the set of natural numbers. A *function* is a mapping from a subset of  $N$  into  $N$ , and a *total function* is a mapping from  $N$  into  $N$ . A *class* is any collection of total functions. A class is called *special* in case it is nonempty and has no recursive member. Two classes are called *degree-isomorphic* if there is a one-to-one correspondence between them which preserves (Turing) degree.

A *theory* is any deductively closed set of sentences in a countable language. We often view theories as sets of numbers via Gödel-numbering.

A *string* is a function whose domain is a finite initial segment of  $N$ . If  $f$  is a function and  $j \in N$ , we define  $[f]_j$  to be the restriction of  $f$  to  $\{k: k < j\}$ . Thus if  $f$  is total,  $[f]_j$  is a string for all  $j$ . If  $S$  is a set of strings, we define  $S^*$  to be the class of total functions  $f$  such that  $[f]_j \in S$  for all  $j \in N$ . If  $S$  is a recursive set of strings (under some Gödel numbering),  $S^*$  is called a  $\Pi_1^0$ -class. Any  $\Pi_1^0$  class may be put in the form  $T^*$ , where  $T$  is a recursive set of strings closed under initial substring, i.e., a *recursive tree*. Then  $T^*$  may be viewed intuitively as the class of all infinite paths through the tree  $T$ .

A class is called *recursively bounded* if there exists a recursive function which majorizes all of its members. (We say  $g$  majorizes  $f$

if  $g(n) \geq f(n)$  for all  $n \in N$ .) We identify sets with their characteristic functions so that any collection of sets is a recursively bounded class. In the converse direction, every recursively bounded  $\Pi_1^0$  class (of functions) is degree-isomorphic to a  $\Pi_1^0$  class of sets. This may be proved by a simple coding argument or by appeal to [4, Proposition 6.5] where it is shown that every recursively bounded  $\Pi_1^0$  class is degree-isomorphic to the class of complete extensions of some axiomatizable theory. Thus, for our purposes, there is no essential distinction between recursively bounded  $\Pi_1^0$  classes and  $\Pi_1^0$  classes of sets.

If  $A$  is an infinite set, the principal function of  $A$  (denoted  $p_A$ ) is the total function which enumerates  $A$  in increasing order. For sets  $A, B$  the notation  $A \leq_r B$  means that  $A$  is recursive in  $B$ , and similarly for functions. We assume a standard indexing and enumeration of all r.e. sets. The  $e^{\text{th}}$  r.e. set is denoted  $W_e$  and the finite subset of  $W_e$  enumerated after  $s$  steps is denoted  $W_e^s$ .

In general, there is a strong distinction between recursively bounded  $\Pi_1^0$  classes and arbitrary  $\Pi_1^0$  classes, but the first theorem indicates a point of similarity.

**THEOREM 1.** *For any special  $\Pi_1^0$  class  $\mathcal{S}$  there is a special recursively bounded  $\Pi_1^0$  class  $\mathcal{T}$  such that  $\{f: f \in \mathcal{S}\} \equiv \{f: f \in \mathcal{T}\}$ , where  $f$  denotes the degree of  $f$ .*

*Proof.* Let us say that a string has *type 1* if its range is contained in  $\{0, 1\}$  and *type 2* if its range is disjoint from  $\{0, 1\}$ . Clearly there is a recursive set  $T_2$  of strings of type 2 such that  $T_2^*$  is degree-isomorphic to  $\mathcal{S}$ . Let  $T_1$  be any recursive set of strings of type 1 such that  $T_1^*$  is a special  $\Pi_1^0$  class of sets. (For instance,  $T_1^*$  could be the class of complete extensions of some axiomatizable essentially undecidable theory [14].)

If  $\sigma, \tau$  are strings, we write  $\sigma * \tau$  for the string obtained by viewing  $\sigma$  and  $\tau$  as finite sequences and then concatenating them. If  $\sigma * \tau$  is a string,  $\sigma$  may be "factored" as follows:

$$\sigma = \sigma_1 * \tau_1 * \sigma_2 * \tau_2 * \cdots * \tau_n$$

where for  $1 \leq i \leq n$ ,  $\sigma_i$  is of type 2 and  $\tau_i$  is of type 1. To make the factorization unique we also require that at most  $\sigma_1, \tau_n$  be empty and  $n > 0$ . Now define  $t(\sigma)$  (the 1-tail of  $\sigma$ ) to be  $\tau_n$  and  $s(\sigma)$  (the 2-skeleton of  $\sigma$ ) to be  $\sigma_1 * \sigma_2 * \cdots * \sigma_n$ .

We define  $T$  to be the set of strings  $\sigma$  such that

- (i)  $t(\sigma) \in T_1$  and  $s(\sigma) \in T_2$
- (ii)  $\sigma(n) \leq n + 1$  for all  $n$  in domain of  $\sigma$ .

We claim that if  $\mathcal{F} = T^*$ , then  $\mathcal{F}$  satisfies the requirements of the theorem.  $T^*$  is clearly a recursively bounded  $\Pi_1^0$  class. To show that  $T^*$  has no recursive member it suffices to show that if  $f \in T^*$  then there exists  $g \in T_1^* \cup T_2^*$  such that  $g \leq_T f$ . (Recall that neither  $T_1^*$  nor  $T_2^*$  has any recursive members.) Assume  $f \in T^*$ .

*Case 1.*  $\{n: f(n) > 1\}$  is infinite. Let  $g$  be the "2-skeleton" of  $f$ . More precisely, let  $g = f \circ h$ , where  $h$  is the principal function of  $\{n: f(n) > 1\}$ . Then  $g \leq_T f$  and  $g \in T_2^*$  because for each  $n$  there exists  $k$  such that  $[g]_n = s([f]_k)$ . Since  $[f]_k \in T$  for all  $k$ ,  $[g]_n \in T_2$  for all  $n$ .

*Case 2.*  $\{n: f(n) > 1\}$  is finite. Let  $g$  be the "1-tail" of  $f$ . More precisely, let  $i_0$  be the least number  $j$  such that  $f(i) \in \{0, 1\}$  for all  $i \geq j$  and define  $g(n) = f(i_0 + n)$  for all  $n$ . Then  $g \leq_T f$  and  $g \in T_1^*$  because for each  $n$  there exists  $k$  such that  $[g]_n = t([f]_k)$ . This completes the proof that  $T^*$  has no recursive member. It remains to show that if  $g \in T_2^*$ , then  $T^*$  has a member  $f$  of the same degree as  $g$ . Given  $g \in T_2^*$ , let  $f$  be a function in  $T^*$  whose 2-skeleton (as defined in Case 1) is  $g$ . The function  $f$  is constructed by viewing  $g$  as an infinite sequence and inserting between each pair of consecutive terms a sufficiently long string from  $T_1$  to insure  $f(n) \leq n + 1$ . This is possible because  $T_1$  is an infinite set of strings of type 1. Since the 2-skeleton of  $f$  is  $g$ ,  $g \leq_T f$ . Also  $f \leq_T g$  assuming the strings from  $T_1$  used to construct  $f$  are chosen in an effective manner. Thus  $g$  is the desired function in  $T^*$  of the same degree as  $f$ , so the proof is complete.

**COROLLARY 1.1** *If  $\alpha$  is a degree and  $0 < \alpha \leq 0'$ , then  $\alpha$  is the degree of a member of some special recursively bounded  $\Pi_1^0$  class.*

*Proof.* It is shown in [3, Theorems 4.10 and 4.13], that if  $0 \leq \alpha \leq 0'$  then  $\alpha$  contains a function  $f$  such that  $\{f\}$  is a  $\Pi_1^0$  class. The Corollary follows from this and the Theorem.

**COROLLARY 1.2** *There is an axiomatizable, essentially undecidable theory which has a complete extension of minimal degree.*

*Proof.* Since by [4, Proposition 6.5] each recursively bounded  $\Pi_1^0$  class is degree-isomorphic to the class of complete extensions of some axiomatizable theory, the Corollary follows from Corollary 1.1 and the existence of a minimal degree below  $0'$  [10, Theorem 1].

According to a result of Scott and Tennenbaum [13] the theory in Corollary 1.2 cannot be Peano arithmetic. In fact it is shown in

[4, Corollary 4.4] that if  $\alpha$  is the degree of any complete extension of Peano arithmetic, then any countable partially ordered set can be embedded in the degrees  $< \alpha$ .

The following Corollary extends Theorem 1.

**COROLLARY 1.3** *For any special  $\Pi_2^0$  class  $\mathcal{S}$  there is a special recursively bounded  $\Pi_1^0$  class  $\mathcal{T}$  such that  $\{f: f \in \mathcal{S}\} \subseteq \{f: f \in \mathcal{T}\}$  where  $f$  denotes the degree of  $f$ .*

*Proof.* By [3, Theorem 3.1] each  $\Pi_2^0$  class is degree-isomorphic to some  $\Pi_1^0$  class.

It is not possible to extend Corollary 1.3 by replacing  $\Pi_2^0$  by  $\Pi_3^0$ . This is because by [16, p. 691] the class of all nonrecursive functions is  $\Pi_3^0$  while the class of all functions Turing equivalent to any member of a special  $\Pi_1^0$  class is meager, i.e. of first category [4, Theorem 5.1]. In fact by using the effectiveness of the proof of [4, Theorem 5.1] one may show that there is a degree  $\alpha$  such that  $0 < \alpha \leq 0''$  and no member of any special  $\Pi_1^0$  class has degree  $\alpha$ . Therefore  $0'$  cannot be replaced by  $0''$  in Corollary 1.1.

We now develop notation for functionals which will be useful in the proof of the next theorem. In this we are essentially following Lachlan [5, pp. 537-538], and we refer the reader there for the definitions omitted here. A *functional* is a mapping from the set of all functions into itself. If  $\Phi$  is a functional and  $f$  is a function, we write  $\Phi(f; n)$  for the value (if any) of the function  $\Phi(f)$  at argument  $n$ . We assume that  $\{\Phi_s\}$  is an s.r.e. double sequence of finite functionals such that for each  $e$ ,  $\Phi_s^e$  is increasing in  $s$  with limit denoted  $\Phi_e$ , and every partially recursive functional is  $\Phi_e$  for some  $e$ .

In a sense, the next theorem contrasts with Corollary 1.1, because it shows that there is no single special  $\Pi_1^0$  class of functions sufficiently large to have members of all degrees  $\alpha$ ,  $0 < \alpha \leq 0'$ .

**THEOREM 2.** *If  $\mathcal{P}$  is a special  $\Pi_1^0$  class of functions, then there exists a nonzero r.e. degree  $\alpha$  such that  $\mathcal{P}$  has no member of degree  $\leq \alpha$ .*

*Proof.* Let  $\mathcal{P}$  be  $T^*$ , where  $T$  is a recursive tree. We must construct a nonrecursive r.e. set  $A$  such that for no  $e$  is  $\Phi_e(A) \in T^*$ . Let  $A^s$  be the finite subset of  $A$  enumerated by the end of stage  $s$  of the construction. In order to arrange  $\Phi_e(A) \notin T^*$  we follow the method of Sacks [11, §5, Theorem 1]. That is, we attempt to preserve information about  $A^s$  which forces a long initial subfunction of  $\Phi_e^s(A^s)$  to be in  $T$ . Although at first glance this appears to be just the opposite of what one should do, it has the desired effect

because if  $\Phi_e(A)$  were in  $T^*$ , the values of  $\Phi_e^s(A^s)$  would be so well preserved that  $\Phi_e(A)$  would be recursive, in contradiction to the assumption that  $T^*$  has no recursive member. To insure that  $A$  is nonrecursive, we make  $A$  simple as in [8, §5].

We now define three binary recursive functions  $p, q, r$ .

$$\begin{aligned}
 p(e, s) &= \max\{n: n \leq s \ \& \ [\Phi_e^s(A^s)]_n \in T\} \\
 q(e, s) &= \min\{j: \Phi_e^s([A^s]_j; n) \text{ is defined for all } n < p(e, s)\} \\
 r(e, s) &= \max\{q(e, s'): s' \leq s\}.
 \end{aligned}$$

To see that  $p(e, s)$  is defined for all  $e$  and  $s$ , observe that we may assume without loss of generality that the empty string is in  $T$ . It then follows easily that  $q(e, s)$  and  $r(e, s)$  are also defined. In the construction all numbers  $< r(e, s)$  will be prevented from entering  $A^{s+1}$  (in order to insure  $\Phi_e(A) \notin T^*$  as described previously) unless such a number can be used to make  $W_{e'}^{s+1} \cap A^{s+1} \neq \emptyset$  for some  $e' < e$ . More precisely, the construction is as follows:

*Stage 0.* Let  $A^0 = \emptyset$ .

*Stage  $s + 1$ .* Let  $e_{s+1}$  be the least number  $e \leq s$  such that  $W_e^s \cap A^s = \emptyset$  and  $W_e^s$  contains a number  $u \geq \max(\{r(e', s): e' \leq e\} \cup \{2e\})$ . Let  $A^{s+1} = A^s \cup \{u\}$ , where  $u$  is the least such number for  $e = e_{s+1}$ . (If  $e_{s+1}$  does not exist, let  $A^{s+1} = A^s$ .)

The construction is effective, so  $A$  is r.e.

**LEMMA 2.1.** *No function in  $T^*$  is recursive in  $A$ .*

*Proof.* Assume, for a contradiction, that  $\Phi_e(A) \in T^*$  (and thus  $\Phi_e(A)$  is a total function.)

Then it follows from the continuity of  $\Phi_e$  that  $\lim_s p(e, s) = \infty$ . We claim now that  $\Phi_e(A)$  must be recursive. Let  $t$  be a stage such that for all  $e' < e$ , if  $W_{e'} \cap A \neq \emptyset$ , then  $W_{e'}^t \cap A^t \neq \emptyset$ . Thus for all  $s > t$ , either  $e_s$  is undefined or  $e_s \geq e$ . To compute  $\Phi_e(A; n)$  effectively, find a number  $s_n \geq t$  such that  $n < p(e, s_n)$ . Note that  $\Phi_e(A^{s_n}; n)$  is defined because  $n < p(e, s_n)$ . We claim in fact that  $\Phi_e(A^{s_n}; n) = \Phi_e(A; n)$ . To show this it suffices to prove that no number  $u < q(e, s_n)$  enters  $A$  after stage  $s_n$ . But if  $u \in A^{s+1} - A^s$  and  $s + 1 > s_n$ , then  $e_{s+1} \geq e$  and so  $u \geq r(e, s) \geq q(e, s_n)$  by the construction. Since  $\Phi_e(A^{s_n}; n)$  is effectively computable from  $n$ , it follows that  $\Phi_e(A)$  is recursive.

**LEMMA 2.2.** *For fixed  $e$ ,  $r(e, s)$  is bounded over all  $s$ .*

*Proof.* Let  $n$  be the least number such that  $[\Phi_e(A)]_n \notin T$ . (Such

a number exists by Lemma 2.1). Let  $t$  be as in the proof of Lemma 2.1. By almost exactly the same argument as for Lemma 2.1 one may show, using the assumption that  $[\Phi_e(A)]_n \in T$ , that  $p(e, s) \leq n$  for all  $s \geq t$ . By choice of  $n$ ,  $\Phi_e(A; n')$  is defined for all  $n' < n$ . Choose a number  $j$  such that  $\Phi_e([A]_j; n') = \Phi_e(A; n')$  for all  $n' < n$ . Thus if  $s$  is sufficiently large  $\Phi_e([A^s]_j; n')$  is defined for all  $n' < n$  and hence for all  $n' < p(e, s)$ . Then it follows from the definition of  $q$  that  $q(e, s) \leq j$  for all sufficiently large  $s$  and in turn from the definition of  $r$  that  $r(e, s)$  is bounded over all  $s$ .

LEMMA 2.3. *A is simple.*

*Proof.* Since each r.e. set  $W_e$  “contributes” at most one member  $u \geq 2e$ ,  $A$  contains at most  $e$  elements  $\leq 2e$  and the complement of  $A$  is infinite, just as for Post’s simple set [8, § 5]. Fix a number  $e$ . Let  $j$  be the largest of the numbers  $r(e', s)$  over all  $e' \leq e$  and all  $s$ . The bound  $j$  exists by Lemma 2.2. Then if  $s \geq t$  (where  $t$  is as in Lemma 2.1) and  $W_e^s$  contains a member  $\geq \max\{j, 2e\}$ , then  $W_e^{s+1} \cap A \neq \emptyset$  by the construction. Hence if  $W_e$  is infinite then  $W_e \cap A \neq \emptyset$ . This completes the proof of the theorem.

In Theorem 2 we proved in particular that no special  $\Pi_1^0$  class has members of all nonzero r.e. degrees. On the other hand, we now show that if such a class is recursively bounded, it must have a member of some r.e. degree.

THEOREM 3. *If  $\mathcal{P}$  is a nonempty recursively bounded  $\Pi_1^0$  class of functions,  $\mathcal{P}$  has a member of r.e. degree.*

*Proof.* Let  $f_0$  be the least member of  $\mathcal{P}$  in the lexicographic ordering of functions by first differences. (Since  $\mathcal{P}$  is closed and nonempty,  $f_0$  exists.) Let  $\mathcal{P} = T^*$ , where  $T$  is a recursively bounded recursive tree. Clearly  $f_0 \equiv_T B$ , where  $B$  is the set of nodes on  $T$  which strictly precede  $f_0$  in the lexicographic ordering. To see that  $B$  is r.e. note that the set  $C$  of nodes of  $T$  not extendible to functions of  $T^*$  is r.e. because  $T$  is recursively bounded. If  $lh(\sigma) = lh(\tau)$ , let  $\tau < \sigma$  denote that  $\tau$  lexicographically precedes  $\sigma$ . Since

$$B = \{\sigma : \sigma \in C \ \& \ (\forall \tau)[\tau \in T \ \& \ lh(\sigma) = lh(\tau) \ \& \ \tau < \sigma \Rightarrow \tau \in C]\}$$

and since  $T$  is recursively bounded,  $B$  is r.e.

Conversely to Theorem 3, for every nonrecursive r.e. set  $B$  there is a special  $\Pi_1^0$  class of sets whose lexicographically least element  $f_0$  has the same degree as  $B$ .

In [14, Theorem 2] Shoenfield proved that every nonempty recursively bounded  $\Pi_1^0$  class has a member of degree  $\mathbf{a} < 0'$ . In view of this and Theorem 3 it is natural to conjecture that every nonempty recursively bounded  $\Pi_1^0$  class has a member of r.e. degree  $< 0'$ . We now refute this conjecture.

**THEOREM 4.** *There is a nonempty recursively bounded  $\Pi_1^0$  class  $\mathcal{P}$  such that if  $\mathbf{a}$  is the degree of any member of  $\mathcal{P}$  and  $\mathbf{b}$  is an r.e. degree and  $\mathbf{a} \leq \mathbf{b}$ , then  $\mathbf{b} = 0'$ .*

Before proving Theorem 4, we give a definition and a lemma. A set  $A$  is called *effectively immune* in case  $A$  is infinite and there is a recursive function  $g$  such that for all  $e$ , if  $W_e \subseteq A$  then  $|W_e| < g(e)$ , where  $|W_e|$  is the cardinality of  $W_e$ . (This definition is essentially due to Smullyan [17].) In [6], Martin proved that every r.e. set with effectively immune complement has degree  $0'$ . The following lemma, which is an easy extension of his result, will immediately yield Theorem 4.

**LEMMA 4.1.** *If  $A$  is effectively immune,  $B$  is r.e., and  $A \leq_{\tau} B$ , then  $B$  has degree  $0'$ .*

*Proof.* We only outline the proof, since it is mostly a repetition of Martin's argument in altered format. From the assumptions that  $B$  is r.e.,  $A$  is infinite, and  $A \leq_{\tau} B$  it is easy to show as in [15, Theorem 2] that there is a recursive sequence of recursive functions  $\{\alpha_n\}$  such that  $\lim_n \alpha_n = p_A$  (where  $p_A$  is the principal function of  $A$ ) and  $\{\alpha_n\}$  has a modulus recursive in  $B$ . (cf [15, Theorem 2].) Assume that  $g$  is a recursive function such that if  $W_e \subset A$ , then  $|W_e| < g(e)$ . Let  $C$  be any r.e. set. We shall prove  $C \leq_{\tau} B$ . Fix an enumeration of  $C$  and let  $C^s$  be the finite subset of  $C$  obtained after  $s$  steps. Given a number  $e$ , define an r.e. set  $W_{h(e)}$  as follows. If  $e \in C$ , let  $s(e) = \mu s(e \in C^s)$ . Then let  $W_{h(e)}$  be the range of  $[\alpha_{s(e)}]_{gh(e)}$ . If  $e \notin C$ , let  $W_{h(e)} = \emptyset$ . Note that  $h(e)$  enters (circularly) into the definition of  $W_{h(e)}$ , but this may be justified by the recursion theorem. Also we may assume that  $h$  is recursive.

Let  $r(e)$  be a number such that for  $i \geq r(e)$ ,  $[\alpha_i]_{gh(e)} = [p_A]_{gh(e)}$ . In particular, if  $e \in C$  and  $s(e) \geq r(e)$ , then  $W_{h(e)} \subset A$  and  $|W_{h(e)}| = gh(e)$ , which is impossible. It then follows that

$$e \in C \longleftrightarrow e \in C^{r(e)}$$

for all  $e$ .



However  $r(e)$  may be found recursively in  $B$  because  $g$  and  $h$  are recursive and  $\{\alpha_i\}$  has a modulus recursive in  $B$ . Thus the above equivalence shows that  $C \leq_{\tau} B$ , and the proof of Lemma 4.1 is complete.

*Proof of Theorem 4.* Let  $S$  be Post's simple, nonhypersimple set [8, §5]. As Smullyan [17, p. 893] observed,  $\bar{S}$  is effectively immune. Let  $\{D_{f(k)}\}$  be an s.r.e. sequence of pairwise disjoint sets all intersecting  $\bar{S}$ . Let

$$\mathcal{S} = \{E: E \subset \bar{S} \text{ and } (\forall k)[D_{f(k)} \cap E \neq \emptyset]\}.$$

Then  $\mathcal{S}$  is easily seen to be a nonempty  $\Pi_1^0$  class of sets containing only effectively immune sets. Theorem 4 now follows from Lemma 4.1.

**COROLLARY 4.2.** *There is a degree  $a$  such that  $a' = 0'$  and the only r.e. degree  $\geq a$  is  $0'$ .*

*Proof.* Let  $\mathcal{S}$  be the nonempty recursively bounded  $\Pi_1^0$  class of Theorem 4. Then by [4, Theorem 2.1],  $\mathcal{S}$  has a member of degree  $a$  such that  $a' = 0'$ .

In [19, p. 270] Yates proved that there is a degree  $a < 0'$  such that the only r.e. degrees comparable with  $a$  are 0 and  $0'$ . It is easy to modify his proof so that  $a' = 0'$  also and thus obtain a different proof of Corollary 4.2. On the other hand, we have been unable to modify our proof of Corollary 4.2 to obtain Yates' result. What we lack is a proof of the following conjecture.

*Conjecture.* Every special recursively bounded  $\Pi_1^0$  class  $\mathcal{S}$  contains a member of some degree  $a < 0'$ , such that the only r.e. degree  $\leq a$  is 0.

(If  $0'$  is replaced by  $0''$ , the conjecture follows from [4, Corollary 2.11]).

We now apply Theorem 4 to Peano arithmetic. Considerable further information along these lines may be found in [4].

By the *degree of a countable model*  $M$  we mean the degree of a set which encodes the elements and relations of the model. It is well-known that Peano arithmetic has no recursive nonstandard models. (The standard model is of course recursive.) The proof given in reference [1, p. 48] establishes more. Namely,

**REMARK.** If  $M$  is any nonstandard model of Peano arithmetic, and  $\mathcal{S}$  is any nonempty recursively bounded  $\Pi_1^0$  class, then  $\mathcal{S}$  con-

tains a member recursive in  $M$ .

Scott [12, p. 118] has observed that if  $T$  is any complete extension of Peano arithmetic, then the above remark holds with  $T$  in place of  $M$ . Finally, one can replace "complete extension" by "consistent extension" since it is easy to see that if  $T$  is any consistent extension of Peano arithmetic then there is a complete extension  $T'$  recursive in  $T$  [4, Proposition 6.1]. If we let  $\mathcal{P}$  be the special  $\Pi_1^0$  class of Theorem 4, these observations yield:

**COROLLARY 4.3.** *If  $a$  is the degree of any consistent extension or nonstandard model of Peano arithmetic, and  $b$  is an r.e. degree such that  $a \leq b$ , then  $b = 0'$ .*

In [13] Scott and Tennenbaum announced that no complete extension of Peano arithmetic can have r.e. degree  $< 0'$ . This result, which of course is a consequence of Corollary 4.3 can also be used to refute the conjecture made just before Theorem 4.

**COROLLARY 4.4.** (Scott-Tennenbaum [13]). *There is a complete extension of Peano arithmetic of degree  $0'$ .*

*Proof.* Let  $\mathcal{S}$  be the class of all complete extensions of Peano arithmetic. Then  $\mathcal{S}$  is a nonempty  $\Pi_1^0$  class of sets, so by Theorem 3,  $\mathcal{S}$  has a member of r.e. degree  $b$ . It follows from Corollary 4.3 that  $b = 0'$ .

In [13], Scott and Tennenbaum actually announced the stronger result that if  $a \geq 0'$ , then there is a complete extension of Peano arithmetic of degree  $a$ . This result can be obtained by first using the Friedberg completeness criterion [9, p. 265] to obtain a degree  $b$  such that  $b' = a$  and then relativizing Theorem 3 and Corollary 4.3 to  $b$  with the aid of the two results of Scott stated on [12, p. 118].

All of the results we have obtained here for Peano arithmetic apply as well to any theory in which the provable and refutable formulas are effectively inseparable, such as  $ZF$  set theory (cf [4], Proposition 6.1 or 6.4).

We close with an extension of Theorem 4 in which  $0'$  is replaced by an arbitrary r.e. degree  $c$ . The proof is similar to the former except that Post's simple set is replaced by Yates' simple, nonhyper-simple set of degree  $c$  for  $c \neq 0$  [20, Theorem 2]. An additional difficulty arises in the proof, however, and to overcome it we introduce a method which yields new information about results of Yates and Martin as we discuss at the end of the proof.

**THEOREM 5.** *If  $c$  is any r.e. degree, there is a recursively bounded*

$\Pi_1^0$  class  $\mathcal{P}$  such that the r.e. degrees of members of  $\mathcal{P}$  are precisely the r.e. degrees  $\geq c$ .

*Proof.* Assume  $c \neq 0$  (else the theorem is obvious) and let  $A$  be an r.e. set of degree  $c$ . Following Yates [20, Theorem 2], let  $A = \text{range } f$ , where  $f$  is a 1 – 1 recursive function. At stage  $s$ , for each  $e \leq s$ , if  $W_e^s \cap B^s = \emptyset$  and  $W_e^s$  contains a number  $u_e \geq \max \{2e, f(s)\}$  place the least such  $u_e$  into  $B^{s+1}$ . It follows that  $B$  is simple, non-hypersimple, and  $B \leq_T A$ . Construct  $\mathcal{P}$  as in the proof of Theorem 4 with  $B$  in place of  $S$ . Yates then constructs his simple set  $S$  as the join of  $B$  and a hypersimple set of the same degree as  $A$  to insure that  $A \leq_T S$ . The following lemma shows that this is unnecessary since automatically  $A \leq_T B$ .

**LEMMA 5.1.** *If  $C$  is an r.e. set and  $D$  is an infinite subset of  $\bar{B}$  and  $D \leq_T C$ , then  $A \leq_T C$ .*

*Proof.* As in the proof of Lemma 4.1 there is a recursive sequence of recursive functions  $\{\alpha_n\}$  such that  $\lim_n \alpha_n = p_D$ , the principal function of  $D$ , and  $\{\alpha_n\}$  has a modulus recursive in  $C$ . Given  $e$ , let  $s(e) = \mu s[e = f(s)]$  if  $e \in A$ . Define  $W_{h(e)}$  to be the range of  $[\alpha_{s(e)}]_{2h(e)}$ . (If  $e \notin A$ , let  $W_{h(e)} = \emptyset$ .) Let  $r(e)$  be so large that  $[\alpha_i]_{2h(e)} = [P_D]_{2h(e)}$  for all  $i \geq r(e)$ . Such  $r$  can be found recursively in  $C$  because  $\{\alpha_n\}$  has a modulus recursive in  $C$ .

We cannot argue as in Lemma 4.1 that  $e \in A$  iff  $e \in A^{r(e)}$  since if  $s(e) > r(e)$  we can only conclude that  $W_{h(e)}$ , not  $W_{h(e)}^{s(e)}$ , has a member  $u \geq 2h(e)$ . Thus we must define,

$$\hat{A} = \{e : e \in A - A^{r(e)}\}.$$

*Case 1.*  $\hat{A}$  is finite. Then clearly  $A \leq_T C$ .

*Case 2.*  $\hat{A}$  is infinite. Clearly  $\hat{A}$  is r.e. in  $C$ . Let  $k$  be a given number. Find  $e \in \hat{A}$  such that  $2h(e) > k$ . This  $e$  exists because  $\hat{A}$  is infinite and we may assume that  $h$  is 1 – 1. Also  $e$  may be found recursively in  $C$  because  $\hat{A}$  is r.e. in  $C$ . Let  $s_k$  be a stage such that  $s_k \geq h(e)$  and  $W_{h(e)}^{s_k}$  contains a number  $u \geq 2h(e)$ . ( $W_{h(e)}$  has such a  $u$  because  $e \in \hat{A}$  implies that  $s(e) \geq r(e)$ .) Then  $u$  (or some  $v \leq u$ ) will be used in the construction to make  $W_{h(e)} \cap B \neq \emptyset$ , unless  $f(s) \geq u (> k)$  for all  $s \geq s_k$ . This must be the case because  $W_{h(e)} \subseteq D \subseteq \bar{B}$  since  $e \in \hat{A}$ . Thus,

$$k \in A \iff k \in A^{s_k}.$$

Since  $s_k$  can be found recursively in  $C$ , uniformly in  $k$ ,  $A \leq_T C$ .

*Remark.* The division of the above proof into two cases makes the argument nonuniform. This lack of uniformity may be avoided by an application of the recursion theorem to slightly modify Yates' construction [20, Theorem 2] so that  $\hat{A}$  must be empty.

By Lemma 5.1, the r.e. degrees of members of  $\mathcal{S}$  are all above  $c$ . We complete the proof of Theorem 5 by establishing the converse.

**LEMMA 5.2.** *Given any degree  $a \geq c$ , there is a member  $A \in \mathcal{S}$  of degree  $a$ .*

*Proof.* Let  $B$  be as above, and assume that the strong array  $\{D_{f(n)}\}_{n \in \mathbb{N}}$ , which witnesses the nonhypersimplicity of  $B$ , satisfies  $|D_{f(n)} \cap \bar{B}| \geq 2$  for all  $n$ . Choose a set  $A_1$  of degree  $a$ , and find  $A \in \mathcal{S}$  such that  $A \leq_T A_1$  and  $|D_{f(n)} \cap \bar{A}| = 1$  iff  $n \in A_1$ . Clearly  $A$  has degree  $a$ , so the proof of Theorem 5 is complete.

Frequently in recursion theory, one constructs an r.e. set  $S$  having some property  $P$  and recursive in a given nonrecursive r.e. set  $A$  by enumerating elements in  $A$  for the sake of  $P$  only when  $A$  "permits", i.e., only when a sufficiently small element is enumerated in  $A$ . This clearly guarantees that  $S \leq_T A$ , but the method of Lemma 5.1 sometimes insures that  $A \leq_T S$  also. For example, by the "permitting" method Yates [20, Theorems 1 and 2] constructs a simple set and a semicreative set each recursive in a given nonrecursive r.e. set  $A$ , while Martin [7, Theorems 2 and 4.1] constructs a maximal set and an r.e. set with no maximal superset each recursive in a given dense simple set  $A$ . Yates and Martin also code  $A$  into the constructed set  $S$ , so that  $A \leq_T S$ . By applying the recursion theorem as in Lemma 5.1, one can show that the latter is unnecessary, since in each case automatically  $A \leq_T S$ . In the case of Martin's maximal set construction this saves considerable work as is shown in [2].

These observations suggest a "maximum degree principle" which asserts that if an r.e. set  $S$  is constructed with weak "negative requirements" it automatically has degree  $0'$  and if  $S$  is constructed recursive in  $A$  by Yates' method then  $A \leq_T S$  automatically. Although most finite injury priority constructions of an r.e. set  $S$  can be combined with Yates' method to produce  $S \leq_T A$ , a given nonrecursive r.e. set [18, Theorem 3], it rarely happens that  $A \leq_T S$  automatically unless the negative requirements of the original construction are extremely weak. For example in the original Friedberg-Muchnik construction of incomparable r.e. degrees  $a, b$ , one automatically gets  $a \cup b = 0'$ , but when the incomparable r.e. degrees  $a, b$  are constructed below a fixed nonzero r.e. degree  $c$  by Yates' method, one does not automatically get  $a \cup b = c$  [18].

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Wazir Husan Abdi, <i>A quasi-Kummer function</i> .....	521
Vasily Cateforis, <i>Minimal injective cogenerators for the class of modules of zero singular submodule</i> .....	527
W. Wistar (William) Comfort and Anthony Wood Hager, <i>Cardinality of <math>k</math>-complete Boolean algebras</i> .....	541
Richard Brian Darst and Gene Allen DeBoth, <i>Norm convergence of martingales of Radon-Nikodym derivatives given a <math>\sigma</math>-lattice</i> .....	547
M. Edelstein and Anthony Charles Thompson, <i>Some results on nearest points and support properties of convex sets in <math>c_0</math></i> .....	553
Richard Goodrick, <i>Two bridge knots are alternating knots</i> .....	561
Jean-Pierre Gossez and Enrique José Lami Dozo, <i>Some geometric properties related to the fixed point theory for nonexpansive mappings</i> .....	565
Dang Xuan Hong, <i>Covering relations among lattice varieties</i> .....	575
Carl Groos Jockusch, Jr. and Robert Irving Soare, <i>Degrees of members of <math>\Pi_1^0</math> classes</i> .....	605
Leroy Milton Kelly and R. Rottenberg, <i>Simple points in pseudoline arrangements</i> .....	617
Joe Eckley Kirk, Jr., <i>The uniformizing function for a class of Riemann surfaces</i> .....	623
Glenn Richard Luecke, <i>Operators satisfying condition <math>(G_1)</math> locally</i> .....	629
T. S. Motzkin, <i>On <math>L(S)</math>-tuples and <math>l</math>-pairs of matrices</i> .....	639
Charles Estep Murley, <i>The classification of certain classes of torsion free Abelian groups</i> .....	647
Louis D. Nel, <i>Lattices of lower semi-continuous functions and associated topological spaces</i> .....	667
David Emroy Penney, II, <i>Establishing isomorphism between tame prime knots in <math>E^3</math></i> .....	675
Daniel Rider, <i>Functions which operate on <math>\mathbb{F}L_p(T)</math>, <math>1 &lt; p &lt; 2</math></i> .....	681
Thomas Stephen Shores, <i>Injective modules over duo rings</i> .....	695
Stephen Simons, <i>A convergence theorem with boundary</i> .....	703
Stephen Simons, <i>Maximinimax, minimax, and antiminimax theorems and a result of R. C. James</i> .....	709
Stephen Simons, <i>On Ptak's combinatorial lemma</i> .....	719
Stuart A. Steinberg, <i>Finitely-valued <math>f</math>-modules</i> .....	723
Pui-kei Wong, <i>Integral inequalities of Wirtinger-type and fourth-order elliptic differential inequalities</i> .....	739
Yen-Yi Wu, <i>Completions of Boolean algebras with partially additive operators</i> .....	753
Phillip Lee Zenor, <i>On spaces with regular <math>G_\delta</math>-diagonals</i> .....	759