

# NONTRIVIAL AUTOMORPHISMS OF $\mathcal{P}(\mathbb{N})/[\mathbb{N}]^{<\aleph_0}$ FROM VARIANTS OF SMALL DOMINATING NUMBER

SAHARON SHELAH AND JURIS STEPRĀNS

ABSTRACT. It is shown that if various cardinal invariants of the continuum related to  $\mathfrak{d}$  are equal to  $\aleph_1$  then there is a nontrivial automorphism of  $\mathcal{P}(\mathbb{N})/[\mathbb{N}]^{<\aleph_0}$ . Some of these results extend to automorphisms of  $\mathcal{P}(\kappa)/[\kappa]^{<\kappa}$  if  $\kappa$  is inaccessible.

## 1. INTRODUCTION

A fundamental result in the study of the Čech–Stone compactification, due to W. Rudin [6, 7], is that, assuming the Continuum Hypothesis, there are  $2^c$  autohomeomorphisms of  $\beta\mathbb{N} \setminus \mathbb{N}$  and, hence, there are some that are non-trivial in the sense that they are not induced by any one-to-one function on  $\mathbb{N}$ . While Rudin established his result by showing that for any two P-points of weight  $\aleph_1$  there is an autohomeomorphism sending one to the other, Parovičenko [5] showed that non-trivial autohomeomorphisms could be found by exploiting the countable saturation of the Boolean algebra of clopen subsets of  $\beta\mathbb{N} \setminus \mathbb{N}$  — this is isomorphic to the algebra  $\mathcal{P}(\mathbb{N})/[\mathbb{N}]^{<\aleph_0}$ . Indeed, the duality between Stone spaces of Boolean algebras and algebras of regular open sets shows that the existence of non-trivial autohomeomorphisms of  $\beta\mathbb{N} \setminus \mathbb{N}$  is equivalent to the existence of non-trivial isomorphisms of the Boolean algebra  $\mathcal{P}(\mathbb{N})/[\mathbb{N}]^{<\aleph_0}$  to itself.

**Notation 1.1.** If  $A$  and  $B$  are subsets of  $\kappa$  let  $\equiv_\kappa$  denote the equivalence relation defined by  $A \equiv_\kappa B$  if and only if  $|A \Delta B| < \kappa$  and  $A \subseteq_\kappa B$  will denote the assertion that  $|A \setminus B| < \kappa$ . Let  $[A]_\kappa$  denote the equivalence class of  $A$  modulo  $\equiv_\kappa$  and let  $\mathcal{P}(\kappa)/[\kappa]^{<\kappa}$  denote the quotient algebra of the  $\mathcal{P}(\kappa)$  modulo the congruence relation  $\equiv_\kappa$ . If  $\kappa = \omega$  it is customary to use  $\equiv^*$  instead of  $\equiv_\omega$  and  $\subseteq^*$  instead of  $\subseteq_\omega$ .

**Notation 1.2.** If  $f$  is a function defined on the set  $A$  and  $X \subseteq A$  then the notation  $f(X)$  will be used to denote  $\{f(x) \mid x \in X\}$  in spite of the potential for ambiguity.

**Definition 1.1.** An isomorphism  $\Phi : \mathcal{P}(\kappa)/[\kappa]^{<\kappa} \rightarrow \mathcal{P}(\kappa)/[\kappa]^{<\kappa}$  will be said to be *trivial* if there is a one-to-one function  $\varphi : \kappa \rightarrow \kappa$  such that  $\Phi([A]_\kappa) = [\varphi(A)]_\kappa$  for each  $A \subseteq \kappa$ . Note that if  $\kappa > \omega$  then  $\varphi$  can be taken to be a bijection. The isomorphism  $\Phi$  will be said to be *somewhere trivial* if there is some  $B \in [\kappa]^\kappa$  and a one-to-one function  $\varphi : B \rightarrow \kappa$  such that  $\Phi([A]_\kappa) = [\varphi(A)]_\kappa$  for each  $A \subseteq B$  and  $\Phi$  will be said to be *nowhere trivial* if it is not somewhere trivial.

The question of whether the Continuum Hypothesis, or some other hypothesis, is needed in order to find a non-trivial isomorphism of  $\mathcal{P}(\mathbb{N})/[\mathbb{N}]^{<\aleph_0}$  to itself was settled in the affirmative S. Shelah in [9]. The argument of [9] relies on an iterated oracle chain condition forcing to obtain a model where  $2^{\aleph_0} = \aleph_2$  and every isomorphism of  $\mathcal{P}(\mathbb{N})/[\mathbb{N}]^{<\aleph_0}$  to itself is induced by a one-to-one function from  $\mathbb{N}$  to  $\mathbb{N}$ . The oracle chain condition requires the addition of cofinally many Cohen reals and so  $\mathfrak{d} = \aleph_2$  in this model. Subsequent work has shown that it is also possible to obtain that every isomorphism of  $\mathcal{P}(\mathbb{N})/[\mathbb{N}]^{<\aleph_0}$  is trivial by other approaches [14, 10, 2] but these have always required  $\mathfrak{d} > \aleph_1$  as well. However, it was shown in [11] that this cardinal inequality is not entailed by the non existence of nowhere trivial isomorphisms from  $\mathcal{P}(\mathbb{N})/[\mathbb{N}]^{<\aleph_0}$  to itself — in the model obtained by iterating  $\omega_2$  times Sacks reals there are no nowhere trivial isomorphisms yet  $\mathfrak{d} = \aleph_1$ .

On the other hand, while we now know that the Continuum Hypothesis can not be completely eliminated from Rudin’s result, perhaps it can be weakened to some other cardinal equality such as  $\mathfrak{d} = \aleph_1$ . It will be shown in this article that non-trivial isomorphisms of  $\mathcal{P}(\mathbb{N})/[\mathbb{N}]^{<\aleph_0}$  to itself can indeed be constructed from hypotheses on cardinal arithmetic weaker than  $2^{\aleph_0} = \aleph_1$  and reminiscent of  $\delta = \aleph_1$ . However, it is shown in [8] that it is consistent with set theory that  $\mathfrak{d} = \aleph_1$  yet all isomorphisms of  $\mathcal{P}(\mathbb{N})/[\mathbb{N}]^{<\aleph_0}$  are trivial so some modification of the equality  $\mathfrak{d} = \aleph_1$  will be required.

It will also be shown that natural generalizations of the arguments can be applied to the same question for  $\mathcal{P}(\kappa)/[\kappa]^{<\kappa}$  where  $\kappa$  is inaccessible. The chief interest here is that, unlike  $\mathcal{P}(\mathbb{N})/[\mathbb{N}]^{<\aleph_0}$ , the algebra  $\mathcal{P}(\kappa)/[\kappa]^{<\kappa}$  is not countably saturated if  $\kappa > \omega$  — to see this, simply consider a family  $\{A_n\}_{n \in \omega} \subseteq [\kappa]^\kappa$  such that  $\bigcap_{n \in \omega} A_n = \emptyset$ . In other words, Parovičenko’s transfinite induction argument to construct non-trivial isomorphisms from  $\mathcal{P}(\kappa)/[\kappa]^{<\kappa}$  to itself is not available and some other technique is needed.

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The statement and proof of Lemma 2.1 is provided for all  $\kappa$  and will apply both to the case that  $\kappa = \omega$  and to the case that  $\kappa$  is inaccessible. However, Lemma 3.1 deals only with the case that  $\kappa$  is inaccessible. It is somewhat simpler than the case for  $\omega$  and so is dealt with first because the general approach is similar in the  $\kappa = \omega$  case, but this case requires some technical details not needed in the inaccessible case.

## 2. A SUFFICIENT CONDITION FOR A NON-TRIVIAL ISOMORPHISM

The following lemma provides sufficient conditions for the existence of a nontrivial isomorphism of  $\mathcal{P}(\kappa)/[\kappa]^{<\kappa}$  to itself. The set theoretic requirements for the satisfaction of these conditions will be examined later. The basic idea of the lemma is that an isomorphism of  $\mathcal{P}(\kappa)/[\kappa]^{<\kappa}$  can be approximated by partitioning  $\kappa$  into small sets  $I_\nu$  and constructing isomorphisms from subalgebras of  $\mathcal{P}(I_\nu)$  and taking the union of these. Unless the subalgebras of  $\mathcal{P}(I_\nu)$  are all of  $\mathcal{P}(I_\nu)$ , this union will only be a partial isomorphism. Hence a  $\kappa^+$  length sequence of ever larger families of subalgebras of  $\mathcal{P}(I_\nu)$  is needed to obtain a full isomorphism. In order to guarantee that this isomorphism is not trivial the prediction principle described in Hypothesis 4 of the lemma is needed.

**Lemma 2.1.** *There is a non-trivial automorphism of  $\mathcal{P}(\kappa)/[\kappa]^{<\kappa}$  provided that there is a partition of  $\kappa$  by  $\{I_\nu\}_{\nu \in \kappa}$  such that*

- (1)  $|I_\nu| < \kappa$  for each  $\nu \in \kappa$ .
- (2) For each  $\xi \in \kappa^+$  and  $\nu \in \kappa$  there is a Boolean subalgebra  $\mathfrak{B}_{\xi,\nu}$  of  $\mathcal{P}(I_\nu)$  and an automorphism  $\Phi_{\xi,\nu}$  of  $\mathfrak{B}_{\xi,\nu}$ .
- (3) If  $\xi \in \eta$  then there is  $\iota \in \kappa$  such that  $\mathfrak{B}_{\xi,\nu} \subseteq \mathfrak{B}_{\eta,\nu}$  and  $\Phi_{\xi,\nu} = \Phi_{\eta,\nu} \upharpoonright \mathfrak{B}_{\xi,\nu}$  for all  $\nu \in \kappa \setminus \iota$ .
- (4) For any one-to-one  $F : \kappa \rightarrow \kappa$  there are  $\xi \in \kappa^+$  and cofinally many  $\nu \in \kappa$  for which there is an atom  $a \in \mathfrak{B}_{\xi,\nu}$  and  $\iota \in a$  such that  $F(\iota) \notin \Phi_{\xi,\nu}(a)$ .
- (5) For any  $A \subseteq \kappa$  there are  $\xi \in \kappa^+$  and  $\iota$  in  $\kappa$  such that  $A \cap I_\nu \in \mathfrak{B}_{\xi,\nu}$  for all  $\nu \in \kappa \setminus \iota$ .

*Proof.* Define

$$\Phi([A]_\kappa) = \lim_{\xi \rightarrow \kappa^+} \left[ \bigcup_{\nu \in \kappa} \Phi_{\xi,\nu}(A \cap I_\nu) \right]_\kappa$$

and begin by observing that this is well defined. To see this, it must first be observed that given  $A$  and  $B$  such that  $|A \Delta B| < \kappa$  there is  $\alpha \in \kappa^+$  such that for all  $\xi > \alpha$  and for all  $\nu$  in a final segment of  $\kappa$  the equation

$$\Phi_{\xi,\nu}(A \cap I_\nu) = \Phi_{\xi,\nu}(B \cap I_\nu)$$

is defined and valid by Hypothesis 5. From Hypothesis 3 it then follows that if  $\xi$  and  $\eta$  are greater than  $\alpha$  then

$$\bigcup_{\nu \in \kappa} \Phi_{\xi,\nu}(A \cap I_\nu) \equiv_\kappa \bigcup_{\nu \in \kappa} \Phi_{\eta,\nu}(B \cap I_\nu)$$

and, hence,  $\Phi([A]_\kappa)$  is well defined. Since each  $\Phi_{\xi,\nu}$  is an automorphism it follows that  $\Phi$  is an automorphism of  $\mathcal{P}(\kappa)/[\kappa]^\kappa$ .

To see that  $\Phi$  is non-trivial, suppose that there is a one-to-one function  $F : \kappa \rightarrow \kappa$  such that  $F(A) \in \Phi([A]_\kappa)$  for all  $A \subseteq \kappa$ . Using Hypothesis 4 choose  $\xi \in \kappa^+$  for which there is  $Z \in [\kappa]^\kappa$  and atoms  $a_\nu \in \mathfrak{B}_{\xi,\nu}$  and  $j_\nu \in a_\nu$  such that  $F(j_\nu) \notin \Phi_{\xi,\nu}(a_\nu)$  for each  $\nu \in Z$ . Let  $W \in [Z]^\kappa$  be such that for each  $\nu \in W$ , if  $F(j_\nu) \in I_\mu$  and  $\mu \neq \nu$  then  $\mu \notin W$ . Let  $A = \bigcup_{\nu \in W} a_\nu$ . It follows from Hypothesis 3 that for any  $\eta \geq \xi$

$$\{F(j_\nu) \mid \nu \in W\} \cap \bigcup_{\nu \in W} \Phi_{\eta,\nu}(a_\nu) \equiv_\kappa \{F(j_\nu) \mid \nu \in W\} \cap \bigcup_{\nu \in W} \Phi_{\xi,\nu}(a_\nu) \equiv_\kappa \emptyset$$

and, hence,  $F(A) \notin \Phi([A]_\kappa)$ . □

## 3. WHEN ARE THE HYPOTHESES OF LEMMA 2.1 SATISFIED?

In answering a question of A. Blass concerning the classification of cardinal invariants of the continuum based on the Borel hierarchy M. Goldstern and S. Shelah introduced a family of cardinal invariants called  $\mathbf{c}(f, g)$  defined to be the least number of uniform trees with  $g$ -splitting needed to cover a uniform tree with  $f$ -splitting [3] and showed that uncountably many of these can be distinct simultaneously. The following definition is very closely related to this as well as to the notion of a *slalom* found in [1].

**Definition 3.1.** Given functions  $f$  and  $g$  from  $\mathbf{cof}(\kappa)$  to  $\kappa$  such that  $g(\xi)$  is a cardinal for each  $\xi \in \mathbf{cof}(\kappa)$  then let  $\mathfrak{d}_{f,g}$  be the least cardinal of a family  $\mathcal{D} \subseteq \prod_{\nu \in \kappa} [f(\nu)]^{g(\nu)}$  such that for every  $F \in \prod_{\nu \in \kappa} f(\nu)$  there is  $G \in \mathcal{D}$  such that  $F(\nu) \in G(\nu)$  for all  $\nu$ . Given a uniform filter  $\mathcal{F}$  on  $\kappa$  define  $\mathfrak{d}_{f,g}(\mathcal{F})$  to be the least cardinal of a family  $\mathcal{D} \subseteq \prod_{\nu \in \kappa} [f(\nu)]^{g(\nu)}$  such that for every  $F \in \prod_{\nu \in \kappa} f(\nu)$  there is  $G \in \mathcal{D}$  and  $X \in \mathcal{F}$  such that  $F(\nu) \in G(\nu)$  for all  $\nu \in X$ . (So  $\mathfrak{d}_{f,g} = \mathfrak{d}_{f,g}(\mathcal{F})$  where  $\mathcal{F}$  is the filter dual to  $[\kappa]^{<\kappa}$ .)

**Lemma 3.1.** *Let  $\kappa$  be inaccessible and  $f : \kappa \rightarrow \kappa$  and  $g : \kappa \rightarrow \kappa$  be functions such that:*

- both  $f$  and  $g$  take their values in the set of cardinals

- $\lim_{\nu \rightarrow \kappa} g(\nu) = \kappa$
- $2^{g(\nu)} < |f(\nu)|$  for all  $\nu \in \kappa$
- $\mathfrak{d}_{2^f, g}(\mathcal{F}) = \kappa^+$  for some filter  $\mathcal{F}$  generated by a  $\subseteq_\kappa$ -descending tower of length  $\kappa^+$

then the hypotheses of Lemma 2.1 hold.

*Proof.* Given the hypothesis, it may be assumed that there are  $\subseteq_\kappa$ -descending sets  $\{X_\xi\}_{\xi \in \kappa^+} \subseteq \mathcal{F}$  and functions  $\{G_\xi\}_{\xi \in \kappa^+} \subseteq \prod_{\nu \in \kappa} [2^{f(\nu)}]^{g(\nu)}$  such that for every  $F \in \prod_{\nu \in \kappa} 2^{f(\nu)}$  there is  $\xi \in \kappa^+$  such that  $F(\nu) \in G_\xi(\nu)$  for all  $\nu$  in a final segment of  $X_\xi$ . (This is done simply by reindexing so that for all  $\xi \in \kappa^+$  there are cofinally many  $\eta \in \kappa^+$  such that  $G_\xi = G_\eta$ .) Moreover, by a diagonal argument using the fact that  $\lim_{\nu \rightarrow \kappa} g(\nu) = \kappa$  it can be assumed that if  $\xi \in \eta$  then  $G_\xi(\nu) \subseteq G_\eta(\nu)$  for a final segment of  $\nu \in X_\eta$ . (This is the part of the argument that does not extend to the case  $\kappa = \omega$ .)

Now let  $\{I_\nu\}_{\nu \in \kappa}$  partition  $\kappa$  such that  $|I_\nu| = f(\nu)$  and let  $\{\theta_{\iota, \nu}\}_{\iota \in 2^{f(\nu)}}$  enumerate all permutations of  $I_\nu$ . Let  $A_\nu : 2^{f(\nu)} \rightarrow \mathcal{P}(I_\nu)$  be a bijection. Let  $A_{0, \nu}$  and  $A_{1, \nu}$  partition  $I_\nu$  into two sets of cardinality  $f(\nu)$  and let  $\varphi_{0, \nu}$  be an involution of  $I_\nu$  interchanging  $A_{0, \nu}$  and  $A_{1, \nu}$ . For  $\nu \in X_0$  let  $\mathfrak{B}_{0, \nu} = \{\emptyset, I_\nu, A_{0, \nu}, A_{1, \nu}\}$  and let  $\Phi_{0, \nu}$  be the automorphism of  $\mathfrak{B}_{0, \nu}$  induced by  $\varphi_{0, \nu}$ . For  $\nu \in \kappa \setminus X_0$  let  $\mathfrak{B}_{0, \nu} = \mathcal{P}(I_\nu)$  and let  $\Phi_{0, \nu}$  be the identity. As the induction hypothesis assume Condition 3 of Lemma 2.1 holds and that, in addition,

- $\mathcal{A}_{\xi, \nu}$  are the atoms of  $\mathfrak{B}_{\xi, \nu}$  and  $\mathcal{A}_{\xi, \nu}$  generate  $\mathfrak{B}_{\xi, \nu}$
- $\mathcal{A}_{\xi, \nu}$  is a partition of  $I_\nu$
- $|\mathcal{A}_{\xi, \nu}| \leq 2^{g(\nu)}$  provided that  $\nu \in X_\xi$
- for  $\nu \in X_\xi$  there are involutions  $\varphi_{\xi, \nu}$  of  $I_\nu$  that induce  $\Phi_{\xi, \nu}$ .

If  $\mathfrak{B}_{\xi, \nu}$ ,  $\mathcal{A}_{\xi, \nu}$ ,  $\varphi_{\xi, \nu}$  and  $\Phi_{\xi, \nu}$  have been defined for all  $\xi$  less than the limit ordinal  $\eta$  then a standard diagonalization yields  $\mathfrak{B}_{\eta, \nu}$ ,  $\mathcal{A}_{\eta, \nu}$ ,  $\varphi_{\eta, \nu}$  and  $\Phi_{\eta, \nu}$ .

Therefore assume that  $\mathfrak{B}_{\xi, \nu}$ ,  $\mathcal{A}_{\xi, \nu}$ ,  $\varphi_{\xi, \nu}$  and  $\Phi_{\xi, \nu}$  have been defined. Let  $\mathcal{A}_{\xi+1, \nu}^*$  be the atoms generated by  $\mathcal{A}_{\xi, \nu}$  and  $\{A_\nu(\iota), \varphi_{\xi, \nu}(A_\nu(\iota))\}_{\iota \in G_{\xi+1}(\nu)}$  — in other words,  $\mathcal{A}_{\xi+1, \nu}^*$  consists of intersections of maximal centred subfamilies of

$$\mathcal{A}_{\xi, \nu} \cup \{A_\nu(\iota) \cap \varphi_{\xi, \nu}(A_\nu(\iota)), I_\nu \setminus (A_\nu(\iota) \cup \varphi_{\xi, \nu}(A_\nu(\iota))), \varphi_{\xi, \nu}(A_\nu(\iota)) \setminus A_\nu(\iota), A_\nu(\iota) \setminus \varphi_{\xi, \nu}(A_\nu(\iota))\}_{\iota \in G_{\xi+1}(\nu)}.$$

Observe that since the elements of  $\mathcal{A}_{\xi, \nu}$  are pairwise disjoint, at most one them can belong to a centred family and so  $|\mathcal{A}_{\xi+1, \nu}^*| \leq |\mathcal{A}_{\xi, \nu}| 2^{g(\nu)} \leq 2^{g(\nu)}$  for all  $\nu$  in a final segment of  $X_\xi$ . Moreover,  $\mathcal{A}_{\xi+1, \nu}^*$  is a partition of  $I_\nu$ . Since  $f(\nu) > 2^{g(\nu)}$  there must be for each  $\nu \in X_\xi$  some  $a_\nu \in \mathcal{A}_{\xi+1, \nu}^*$  such that  $|a_\nu| > g(\nu)$ . For each  $\nu \in X_{\xi+1}$  let  $\varphi : a_\nu \rightarrow \varphi_{\xi, \nu}(a_\nu)$  be any bijection such that for each  $\iota \in G_{\xi+1}(\nu)$  there is some  $k_{\iota, \nu} \in a_\nu$  such that  $\varphi(k_{\iota, \nu}) \neq \theta_{\iota, \nu}(k_{\iota, \nu})$ . Now for  $\nu \in X_{\xi+1}$  let

$$\mathcal{A}_{\xi+1, \nu} = (\mathcal{A}_{\xi+1, \nu}^* \setminus \{a_\nu\}) \cup \{\{k_{\iota, \nu}\} \mid \iota \in G_{\xi+1}(\nu)\} \cup \{a_\nu \setminus \{k_{\iota, \nu}\}_{\iota \in G_{\xi+1}(\nu)}\}$$

and note that  $\mathcal{A}_{\xi+1, \nu}$  is also a partition. Let  $\varphi_{\xi+1, \nu}$  be defined by

$$\varphi_{\xi+1, \nu}(z) = \begin{cases} \varphi_{\xi, \nu}(z) & \text{if } z \notin a_\nu \cup \varphi_{\xi, \nu}(a_\nu) \\ \varphi(z) & \text{if } z \in a_\nu \\ \varphi^{-1}(z) & \text{if } z \in \varphi_{\xi, \nu}(a_\nu) \end{cases}$$

and let  $\Phi_{\xi+1, \nu}$  be induced by  $\varphi_{\xi+1, \nu}$ . Let  $\mathfrak{B}_{\xi+1, \nu}$  be the Boolean algebra generated by the atoms  $\mathcal{A}_{\xi+1, \nu}$ . On the other hand, for  $\nu \in \omega \setminus X_{\xi+1}$  let  $\mathfrak{B}_{\xi+1, \nu} = \mathcal{P}(I_\nu)$  and let  $\Phi_{\xi+1, \nu}$  be induced by  $\varphi_{\xi, \nu}$ . It is immediate for each  $\nu \in \kappa$  that  $\mathfrak{B}_{\xi, \nu} \subseteq \mathfrak{B}_{\xi+1, \nu}$  and that  $\Phi_{\xi+1, \nu} \upharpoonright \mathfrak{B}_{\xi, \nu} = \Phi_{\xi, \nu}$ . Moreover,

$$|\mathcal{A}_{\xi+1, \nu}| \leq |\mathcal{A}_{\xi+1, \nu}^*| + g(\nu) \leq 2^{g(\nu)}$$

for all  $\nu$  in a final segment of  $X_{\xi+1}$  as required.

To see that Hypothesis 4 of Lemma 2.1 holds let  $F : \mathbb{N} \rightarrow \mathbb{N}$  be one-to-one. If there are cofinally many  $\nu$  such that there is  $z_\nu \in I_\nu$  such that  $F(z_\nu) \notin I_\nu$  then let  $\xi = 0$  and, without loss of generality, it may be assumed that  $z_\nu$  belongs to the atom  $A_{0, \nu}$  of  $\mathfrak{B}_{0, \nu}$  for cofinally many  $\nu$ . Since  $\varphi_{0, \nu}(A_{0, \nu}) = A_{1, \nu} \subseteq I_\nu$  it is clear that  $F(z_\nu) \notin \varphi_{0, \nu}(A_{0, \nu})$ . If, on the other hand,  $F(I_\nu) \subseteq I_\nu$  for all  $\nu$  in a final segment of  $\kappa$  then  $F \upharpoonright I_\nu = \theta_{J(\nu), \nu}$  for some  $J(\nu)$  also for a final segment. There is then some  $\xi \in \kappa^+$  such that  $J(\nu) \in G_\xi(\nu)$  for all  $\nu$  in a final segment of  $X_\xi$  and it may as well be assumed this is a successor. By construction, for all  $\nu$  in a final segment  $X_\xi$  there is a singleton  $\{k\} \in \mathcal{A}_{\xi, \nu}$  such that  $\varphi_{\xi, \nu}(\{k\}) = \{\varphi_{\xi, \nu}(k)\}$  and  $\varphi_{\xi, \nu}(k) \neq \theta_{J(\nu), \nu}(k)$ .

Finally, to see that Hypothesis 5 of Lemma 2.1 holds let  $A \subseteq \kappa$ . Let  $F \in \prod_{\nu \in \kappa} 2^{f(\nu)}$  be such that  $A \cap I_\nu = A_\nu(F(\nu))$  for all  $\nu$ . By the hypothesis of Lemma 3.1 there is  $\xi \in \kappa^+$  such that  $F(\nu) \in G_\xi(\nu)$  for all  $\nu \in X_\xi$ . It follows that  $A \cap I_\nu = A_\nu(F(\nu)) \in \mathfrak{B}_\xi(\nu)$  for all  $\nu$  in a final segment of  $X_\xi$ . Since  $\mathfrak{B}_{\xi, \nu} = \mathcal{P}(I_\nu)$  if  $\nu \notin X_\xi$  it follows that there is some  $\iota \in \kappa$  such that  $A \cap I_\nu \in \mathfrak{B}_{\xi, \nu}$  for all  $\nu \geq \iota$ .  $\square$

4. THE SPECIAL CASE OF  $\kappa = \omega$ 

The proof of Lemma 3.1 does not apply to  $\kappa = \omega$  because it relies on the fact that  $\mu \cdot \mu = \mu$  if  $\mu$  is an infinite cardinal. This is used to reduce to the case  $G_\xi(\nu) \subseteq G_\eta(\nu)$  for most  $\nu$  if  $\xi \in \eta$ . The first part of the proof of Lemma 4.1 corrects this, but the general outline of the proof is the same as that of Lemma 3.1.

**Lemma 4.1.** *If there are functions  $f : \mathbb{N} \rightarrow \mathbb{N}$  and  $g : \mathbb{N} \rightarrow \mathbb{N}$  such that for all  $k \in \mathbb{N}$*

$$\lim_{n \rightarrow \infty} \frac{f(n)}{g(n)k^{g(n)}} = \infty$$

*and if  $\mathfrak{d}_{f!,g}(\mathcal{F}) = \aleph_1$  for some filter  $\mathcal{F}$  generated by a  $\subseteq^*$ -descending tower of length  $\omega_1$  then the hypotheses of Lemma 2.1 hold.*

*Proof.* Given the hypothesis, it may be assumed that there are  $\subseteq^*$ -descending sets  $\{X_\xi\}_{\xi \in \omega_1} \subseteq \mathcal{F}$  and functions  $\{G_\xi\}_{\xi \in \omega_1} \subseteq \prod_{n \in \omega} [f(n)]^{g(n)}$  such that for every  $F \in \prod_{n \in \omega} f(n)!$  there is  $\xi \in \omega_1$  such that  $F(n) \in G_\xi(n)$  for all but finitely many  $n \in X_\xi$ . (This is done simply by reindexing so that for all  $\xi \in \omega_1$  there are cofinally many  $\eta \in \omega_1$  such that  $G_\xi = G_\eta$ .)

It will first be shown that it can be assumed that there are functions,  $\bar{g}, h_\xi : \mathbb{N} \rightarrow \mathbb{N}$  and  $H_\xi \in \prod_{n \in \mathbb{N}} [f(n)]^{h_\xi(n)}$  for  $\xi \in \omega_1$  such that

- (1)  $\lim_{n \rightarrow \infty} \frac{f(n)}{\bar{g}(n)2^{\bar{g}(n)}} = \infty$
- (2) if  $\xi \in \eta \in \omega_1$  then  $4h_\xi \leq^* h_\eta \leq \bar{g}$
- (3) if  $\xi \in \eta \in \omega_1$  then  $4h_\xi \leq^* h_\eta \leq \bar{g}$
- (4) if  $\xi \in \eta \in \omega_1$  then  $H_\xi(n) \subseteq H_\eta(n)$  for all but finitely many  $n$
- (5) if  $F \in \prod_{n \in \mathbb{N}} f(n)!$  and  $F(n) \in G_\xi(n)$  for all but finitely many  $n \in X_\xi$  then also  $F(n) \in H_\xi(n)$  for all but finitely many  $n \in X_\xi$ .

To see this note that the hypothesis that  $\lim_{n \rightarrow \infty} f(n)/g(n)k^{g(n)} = \infty$  for all  $k$  makes it possible to choose  $h : \mathbb{N} \rightarrow \mathbb{N}$  such that

$$\lim_{n \rightarrow \infty} \frac{f(n)}{g(n)h(n)2^{g(n)h(n)}} = \infty$$

and  $\lim_{n \rightarrow \infty} h(n) = \infty$ . This makes it possible to find  $\bar{h}_\xi : \mathbb{N} \rightarrow \mathbb{N}$  for  $\xi \in \omega_1$  such that if  $\xi \in \eta$  then  $4\bar{h}_\xi(n) < \bar{h}_\eta(n) < h(n)$  for all but finitely many  $n \in \mathbb{N}$ . Let  $\bar{g}(n) = h(n)g(n)$  and note that it can be assumed that  $f(n) > \bar{g}(n)2^{\bar{g}(n)}$  for all  $n \in \mathbb{N}$ . Define  $h_\xi(n) = g(n)\bar{h}_\xi(n)$  and observe that if  $\xi \in \eta \in \omega_1$  then

$$4h_\xi(n) = 4\bar{h}_\xi(n)g(n) \leq \bar{h}_\eta g(n) \leq h(n)g(n) = \bar{g}(n)$$

for all but finitely many  $n$ .

Let  $H_0(n) = G_0(n)$ . Given  $H_\xi$  satisfying Conditions 4 and 5, define  $H_{\xi+1}(n) = H_\xi(n) \cup G_{\xi+1}(n)$  and note that

$$|H_{\xi+1}(n)| \leq |H_\xi(n)| + |G_{\xi+1}(n)| \leq h_\xi(n) + g(n) \leq (\bar{h}_\xi(n) + 1)g(n) \leq \bar{h}_{\xi+1}(n)g(n) = h_{\xi+1}(n).$$

On the other hand, if  $\eta$  is a limit ordinal and  $H_\xi$  satisfying the desired requirements have been chosen for  $\xi \in \eta$ , then a diagonalization argument yields  $H_\eta$  such that  $|H_\eta(n)| = h_\eta(n)$  and  $H_\xi(n) \subseteq H_\eta(n)$  for all but finitely many  $n$  for each  $\xi \in \eta$ . Hence  $g$  can be replaced by  $\bar{g}$  and the  $h_\xi$  and  $H_\xi$  satisfy Conditions 3, 4 and 5.

Now let  $\{I_n\}_{n \in \omega}$  partition  $\mathbb{N}$  such that  $|I_n| = f(n)$  and let  $\{\theta_{j,n}\}_{j \in f(n)!$  enumerate all permutations of  $I_n$ . Let  $A_n : f(n)! \rightarrow \mathcal{P}(I_n)$  be a surjection. Without loss of generality,  $f(n)$  is even for each  $n$ . So let  $A_{0,n}$  and  $A_{1,n}$  partition  $I_n$  into two equal sized sets and let  $\varphi_{0,n}$  be an involution of  $I_n$  interchanging  $A_{0,n}$  and  $A_{1,n}$ . For  $n \in X_0$  let  $\mathfrak{B}_{0,n} = \{\emptyset, I_n, A_{0,n}, A_{1,n}\}$  and let  $\Phi_{0,n}$  be the automorphism of  $\mathfrak{B}_{0,n}$  induced by  $\varphi_{0,n}$ . For  $n \in \omega \setminus X_0$  let  $\mathfrak{B}_{0,n} = \mathcal{P}(I_n)$  and let  $\Phi_{0,n}$  be the identity. As the induction hypothesis assume Condition 3 of Lemma 2.1 holds and that, in addition,

- (6)  $\mathcal{A}_{\xi,n}$  are the atoms of  $\mathfrak{B}_{\xi,n}$  and that  $|\mathcal{A}_{\xi,n}| \leq 2^{4h_\xi(n)}$  provided that  $n \in X_\xi$
- (7) for  $n \in X_\xi$  there are involutions  $\varphi_{\xi,n}$  of  $I_n$  that induce  $\Phi_{\xi,n}$ .

If  $\mathfrak{B}_{\xi,n}, \mathcal{A}_{\xi,n}, \varphi_{\xi,n}$  and  $\Phi_{\xi,n}$  have been defined for all  $\xi$  less than the limit ordinal  $\eta$  then a standard diagonalization yields  $\mathfrak{B}_{\eta,n}, \mathcal{A}_{\eta,n}, \varphi_{\eta,n}$  and  $\Phi_{\eta,n}$ .

Therefore assume that  $\mathfrak{B}_{\xi,n}, \mathcal{A}_{\xi,n}, \varphi_{\xi,n}$  and  $\Phi_{\xi,n}$  have been defined. Let  $\mathcal{A}_{\xi+1,n}^*$  be the atoms generated by  $\mathcal{A}_{\xi,n}$  and  $\{A_n(j), \varphi_{\xi,n}(A_n(j))\}_{j \in H_{\xi+1}(n)}$  — in other words,  $\mathcal{A}_{\xi+1,n}^*$  consists of intersections of maximal centred subfamilies of  $\mathcal{A}_{\xi,n} \cup \{A_n(j), \varphi_{\xi,n}(A_n(j)), I_n \setminus A_n(j), I_n \setminus \varphi_{\xi,n}(A_n(j))\}_{j \in H_{\xi+1}(n)}$ . Then

$$|\mathcal{A}_{\xi+1,n}^*| \leq |\mathcal{A}_{\xi,n}| 4^{h_{\xi+1}(n)} \leq 2^{4h_\xi(n)} 2^{2h_{\xi+1}(n)} \leq 2^{3h_{\xi+1}(n)} \leq 2^{\bar{g}(n)}$$

for all but finitely many  $n \in X_\xi$ . Since  $f(n) > \bar{g}(n)2^{\bar{g}(n)}$  there must be some  $a_n \in \mathcal{A}_{\xi+1,n}^*$  such that  $|a_n| > \bar{g}(n)$  for each  $n \in X_\xi$ . Let  $\varphi : a_n \rightarrow \varphi_{\xi,n}(a_n)$  be any bijection such that for each  $n \in X_{\xi+1}$  and each  $j \in H_{\xi+1}(n)$  there is some

$k_{j,n} \in a_n$  such that  $\varphi(k_{j,n}) \neq \theta_{j,n}(k_{j,n})$ . Now for  $n \in X_{\xi+1}$  let  $\mathcal{A}_{\xi+1,n} = \mathcal{A}_{\xi+1,n}^* \cup \{\{k_{j,n}\} \mid j \in H_{\xi+1}(n)\}$  and let  $\varphi_{\xi+1,n}$  be defined by

$$\varphi_{\xi+1,n}(z) = \begin{cases} \varphi_{\xi,n}(z) & \text{if } z \notin a_n \cup \varphi_{\xi,n}(a_n) \\ \varphi(z) & \text{if } z \in a_n \\ \varphi^{-1}(z) & \text{if } z \in \varphi_{\xi,n}(a_n) \end{cases}$$

and let  $\Phi_{\xi+1,n}$  be induced by  $\varphi_{\xi+1,n}$ . Let  $\mathfrak{B}_{\xi+1,n}$  be the Boolean algebra whose atoms are  $\mathcal{A}_{\xi+1,n}$ . On the other hand, for  $n \in \omega \setminus X_{\xi+1}$  let  $\mathfrak{B}_{\xi+1,n} = \mathcal{P}(I_n)$  and let  $\Phi_{\xi+1,n}$  be induced by  $\varphi_{\xi,n}$ . It is immediate for each  $n \in \omega$  that  $\mathfrak{B}_{\xi,n} \subseteq \mathfrak{B}_{\xi+1,n}$  and that  $\Phi_{\xi+1,n} \upharpoonright \mathfrak{B}_{\xi,n} = \Phi_{\xi,n}$ . Moreover,

$$|\mathcal{A}_{\xi+1,n}| \leq |\mathcal{A}_{\xi+1,n}^*| + h_{\xi+1}(n) \leq 2^{3h_{\xi+1}(n)} + h_{\xi+1}(n) \leq 2^{4h_{\xi+1}(n)}$$

for all but finitely many  $n \in X_{\xi+1}$  as required.

To see that Hypothesis 4 of Lemma 2.1 holds let  $F : \mathbb{N} \rightarrow \mathbb{N}$  be one-to-one. If there are infinitely many  $n$  such that there is  $z_n \in I_n$  such that  $F(z_n) \notin I_n$  then let  $\xi = 0$  and, without loss of generality, it may be assumed that  $z_n$  belongs to the atom  $A_{0,n}$  of  $\mathfrak{B}_{0,n}$  for infinitely many  $n$ . Since  $\varphi_{0,n}(A_{0,n}) = A_{1,n} \subseteq I_n$  it is clear that  $F(z_n) \notin \varphi_{0,n}(A_{0,n})$ . If, on the other hand,  $F(I_n) \subseteq I_n$  for all but finitely many  $n$  then  $F \upharpoonright I_n = \theta_{J(n),n}$  for some  $J(n)$  also for all but finitely many  $n$ . By Condition 5 there is some  $\xi \in \omega_1$  such that  $J(n) \in H_{\xi}(n)$  for all but finitely many  $n \in X_{\xi}$  and Condition 4 allows the assumption that  $\xi$  is a successor. By construction, for all but finitely many  $n \in X_{\xi}$  there is a singleton  $\{k\} \in \mathcal{A}_{\xi,n}$  such that  $\varphi_{\xi,n}(\{k\}) = \{\varphi_{\xi,n}(k)\}$  and  $\varphi_{\xi,n}(k) \neq \theta_{J(n),n}(k)$ .

Finally, to see that Hypothesis 5 of Lemma 2.1 holds let  $A \subseteq \mathbb{N}$ . Let  $F \in \prod_{n \in \mathbb{N}} f(n)!$  be such that  $A \cap I_n = A_n(F(n))$  for all  $n$ . By the hypothesis of Lemma 3.1 there is  $\xi \in \omega_1$  such that  $F(n) \in G_{\xi}(n)$  for all  $n \in X_{\xi}$ . From Condition 5 it follows that  $F(n) \in H_{\xi}(n)$  for all but finitely many  $n \in X_{\xi}$ . Since  $\mathfrak{B}_{\xi,n} = \mathcal{P}(I_n)$  if  $n \notin X_{\xi}$  it follows that  $A \cap I_n \in \mathfrak{B}_{\xi,n}$  for all but finitely many  $n \in \mathbb{N}$ .  $\square$

**Corollary 4.1.** *If  $\mathfrak{d}_{f!,g} = \aleph_1$  then there is a nontrivial isomorphism of  $\mathcal{P}(\mathbb{N})/[\mathbb{N}]^{<\aleph_0}$ .*

*Proof.* In this case let  $\mathcal{F}$  be the co-finite filter and note it is generated by the constant  $\subseteq^*$ -descending sequence all of whose terms are  $\omega$ .  $\square$

**Corollary 4.2.** *If there is an  $\aleph_1$ -generated filter  $\mathcal{F}$  such that  $\mathfrak{d}_{f!,g}(\mathcal{F}) = \aleph_1 \neq \mathfrak{d}$  then there is a nontrivial isomorphism of  $\mathcal{P}(\mathbb{N})/[\mathbb{N}]^{<\aleph_0}$ .*

*Proof.* Let  $\mathcal{F}$  be generated by  $\{X_{\xi}\}_{\xi \in \omega_1}$ . Use Rothberger's argument and  $\aleph_1 \neq \mathfrak{d}$  to construct a  $\subseteq^*$ -descending sequence  $\{Y_{\xi}\}_{\xi \in \omega_1}$  all of whose terms are  $\mathcal{F}$  positive and such that  $Y_{\xi} \subseteq X_{\xi}$ . Let  $\mathcal{F}'$  be generated by  $\{Y_{\xi}\}_{\xi \in \omega_1}$  and note that  $\mathfrak{d}_{f!,g}(\mathcal{F}') = \aleph_1$ .  $\square$

It has to be noted that the hypothesis of Corollary 4.2 is not vacuous in the sense that there are models of set theory in which it holds. For example, in the model obtained by iterating Miller reals  $\omega_2$  times the following hold:

- $\mathfrak{d} = \aleph_2$  because the Miller reals themselves are unbounded by the ground model
- $\mathfrak{d}_{f!,g} = \aleph_1$  for appropriate  $f$  and  $g$  because the Miller partial order satisfies the Laver property
- $\mathfrak{u} = \aleph_1$  because P-points from the ground model generate ultrafilters in the extension.

However there does not seem to be any model demonstrating that the assumption that  $\aleph_1 \neq \mathfrak{d}$  in Corollary 4.2 is essential. It is shown in [8] that it is consistent with set theory that  $\mathfrak{d} = \aleph_1$  yet all automorphisms of  $\mathcal{P}(\mathbb{N})/[\mathbb{N}]^{<\aleph_0}$  are trivial. However,  $\mathfrak{u} = \aleph_2$  in that model because random reals are added cofinally often.

## 5. REMARKS AND QUESTIONS

The first thing to note that there are models where  $\mathfrak{d}_{f!,g} = \aleph_1 < 2^{\aleph_0}$  for  $f$  and  $g$  satisfying the hypotheses of Lemma 4.1 — for example, this is true in the model obtained by either iteratively adding  $\omega_2$  Sacks reals<sup>1</sup> or adding any number of Sacks reals, greater than  $\aleph_1$  of course, side-by-side. Of course  $\mathfrak{d} = \aleph_1$  also in these models. It is therefore of interest to note that the Laver property implies that  $\mathfrak{d}_{f!,g} = \aleph_1$  in the Laver model as well, yet  $\mathfrak{d} = \aleph_2$  in this model. It should also be observed that it is possible for  $\mathfrak{d}_{f!,g}$  to be larger than  $\mathfrak{d}$ . For example, iteratively forcing  $\omega_2$  times with perfect trees  $T$  such that for each  $t \in T$  there is  $s \supseteq t$  such that  $s \cap j \in T$  for each  $j < f(|s|)$  will yield such a model.

The generalization of Sacks reals to uncountable cardinals in [4] establishes that the hypotheses of Lemma 3.1 can be satisfied for uncountable cardinals. However, the following question does not seem to be answered.

**Question 5.1.** Is it consistent for an inaccessible cardinal  $\kappa$  that  $\mathfrak{d}_{f!,g} = \kappa^+$  where  $f(\alpha) = (2^{\aleph_\alpha})^+$  and  $g(\alpha) = \aleph_\alpha$  yet  $\mathfrak{d}(\kappa) > \kappa^+$  where  $\mathfrak{d}(\kappa)$  is the generalization of  $\mathfrak{d}$  to  $\kappa$ ?

<sup>1</sup>See [1] for definitions of terms not defined in this section as well as for details of proofs.

It is worth observing that the isomorphism of Lemma 2.1 is trivial on some infinite sets — indeed, if  $\xi \in \kappa^+$  and  $X \subseteq \mathbb{N}$  are such that  $\{x\}$  belongs to some  $\mathfrak{B}_{\xi,\nu}$  for each  $x \in X$  then  $\Phi$  is trivial on  $\mathcal{P}(X)$ . However, if  $\mathcal{T}(\Phi)$  is defined to be the ideal  $\{X \subseteq \mathbb{N} \mid \Phi \upharpoonright \mathcal{P}(X) \text{ is trivial}\}$  then  $\mathcal{T}(\Phi)$  is a small ideal in the sense that the quotient algebra  $\mathcal{P}(\mathbb{N})/\mathcal{T}(\Phi)$  has large antichains, even modulo the ideal of finite sets — in the terminology of [2], the ideal  $\mathcal{T}(\Phi)$  is not ccc by fin. To see this, simply observe that the proof of Lemma 4.1 actually shows that Hypothesis 4 of Lemma 2.1 can be strengthened to: For any one-to-one  $F: \mathbb{N} \rightarrow \mathbb{N}$  there is  $\xi \in \kappa^+$  such that for all but finitely many  $\nu \in \omega$  there is an atom  $a \in \mathfrak{B}_{\xi,\nu}$  and  $\iota \in a$  such that  $F(\iota) \notin \Phi_{\xi,\nu}(a)$ . It follows that if  $Z \subseteq \mathbb{N}$  is infinite then  $Z^* = \bigcup_{\nu \in Z} I_\nu \notin \mathcal{T}(\Phi)$ . Hence, if  $\mathcal{A}$  is an almost disjoint family of subsets of  $\mathbb{N}$  then  $\{A^* \mid A \in \mathcal{A}\}$  is an antichain modulo the ideal of finite sets.

One should not, therefore, expect to get a nowhere trivial isomorphism by these methods. It is nevertheless, conceivable that there are some other cardinal invariants similar to  $\mathfrak{d}_{f,g}$  that would, when small imply the existence of nowhere trivial isomorphisms of  $\mathcal{P}(\mathbb{N})/[\mathbb{N}]^{<\aleph_0}$ . In this context it is interesting to note that it is at least consistent with small  $\mathfrak{d}$  that there are nowhere trivial isomorphisms.

**Proposition 5.1.** *It is consistent that  $\aleph_1 = \mathfrak{d} \neq 2^{\aleph_0}$  and there is a nowhere trivial isomorphism of  $\mathcal{P}(\mathbb{N})/[\mathbb{N}]^{<\aleph_0}$ .*

*Proof.* The partial order defined Section 2 of [12] will be used<sup>2</sup>. Begin with a model  $V$  satisfying  $2^{\aleph_0} > \aleph_1$  and construct a tower of permutations  $\{(A_\xi, F_\xi, \mathfrak{B}_\xi)\}_{\xi \in \text{Lim}(\omega_1)}$  such that, letting  $\mathfrak{S}_\eta = \{(A_\xi, F_\xi, \mathfrak{B}_\xi)\}_{\xi \in \text{Lim}(\eta)}$  and  $\mathbb{P}_\eta$  be the finite support iteration of partial orders that are  $\mathbb{Q}(\mathfrak{S}_\xi)$  for  $\xi \in \text{Lim}(\eta)$  and Hechler forcing if  $\xi$  is a successor, the following holds for each  $\eta$  and  $G$  that is  $\mathbb{P}_{\omega_1}$  generic over  $V$ :

- $A_\eta = A_{\mathfrak{S}_\eta}[G \cap \mathbb{Q}(\mathfrak{S}_\eta)]$
- $F_\eta = F_{\mathfrak{S}_\eta}[G \cap \mathbb{Q}(\mathfrak{S}_\eta)]$
- $\mathfrak{B}_\eta = \mathcal{P}(\mathbb{N}) \cap V[G \cap \mathbb{P}_\eta]$

The proof of Theorem 2.1 in [12] shows that there is a nowhere trivial isomorphism of  $\mathcal{P}(\mathbb{N})/[\mathbb{N}]^{<\aleph_0}$  in this model and, since  $\mathbb{P}_{\omega_1}$  is ccc, it is also true that  $2^{\aleph_0}$  remains larger than  $\aleph_1$  in the generic extension. The Hechler reals guarantee that  $\mathfrak{d} = \aleph_1$ .  $\square$

It should also be noted that that Lemma 2.1 actually yields  $2^{(\kappa^+)}$  isomorphisms. It is shown in [13] that it is possible to have non-trivial isomorphisms of  $\mathcal{P}(\mathbb{N})/[\mathbb{N}]^{<\aleph_0}$  without having  $2^{\aleph_0}$  such isomorphisms. This motivates the following, somewhat vague, question.

**Question 5.2.** Can there be some variant of  $\mathfrak{d}_{f,g}$  which, when small, yields a non-trivial isomorphism of  $\mathcal{P}(\mathbb{N})/[\mathbb{N}]^{<\aleph_0}$  without yielding the maximal possible number of such?

Given the remarks following Corollary 4.2 it is natural to ask the following.

**Question 5.3.** Is it consistent that  $\mathfrak{d}_{f,g} = \mathfrak{d}$  for  $f$  and  $g$  satisfying the hypothesis of Lemma 4.1 and to have  $\mathfrak{u} = \aleph_1$  and to have that all isomorphisms of  $\mathcal{P}(\mathbb{N})/[\mathbb{N}]^{<\aleph_0}$  are trivial?

As a final remark it will be noted that Corollary 4.1 shows that Theorem 3.1 of [12] cannot be improved to show that in models obtained by iterating Sacks or Silver reals all isomorphisms of  $\mathcal{P}(\mathbb{N})/[\mathbb{N}]^{<\aleph_0}$  are trivial because the equality  $\mathfrak{d}_{f,g} = \aleph_1$  holds in these models for the necessary  $f$  and  $g$ .

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<sup>2</sup>The reader is warned that the word "finite" should be removed from (3) of Definition 2.1 in [12].

INSTITUTE OF MATHEMATICS, HEBREW UNIVERSITY, JERUSALEM, GIVAT RAM, ISRAEL AND DEPARTMENT OF MATHEMATICS, RUTGERS UNIVERSITY, NEW BRUNSWICK, NEW JERSEY, USA

*E-mail address:* `shelah@math.huji.ac.il`

DEPARTMENT OF MATHEMATICS, YORK UNIVERSITY, 4700 KEELE STREET, TORONTO, ONTARIO, CANADA M3J 1P3

*E-mail address:* `steprans@yorku.ca`