THE GENERALIZED BOREL CONJECTURE
AND STRONGLY PROPER ORDERS

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Abstract. The Borel Conjecture is the statement that $C = [\mathbb{R}]^{\omega_1}$, where $C$ is the class of strong measure zero sets; it is known to be independent of ZFC. The Generalized Borel Conjecture is the statement that $C = [\mathbb{R}]^{<c}$. We show that this statement is also independent. The construction involves forcing with an $\omega_2$-stage iteration of strongly proper orders; this latter class of orders is shown to include several well-known orders, such as Sacks and Silver forcing, and to be properly contained in the class of $\omega$-proper, $\omega^n$-bounding orders. The central lemma is the observation that A. W. Miller’s proof that the statement $(\ast)$ “Every set of reals of power $c$ can be mapped (uniformly) continuously onto $[0, 1]$” holds in the iterated Sacks model actually holds in several other models as well. As a result, we show for example that $(\ast)$ is not restricted by the presence of large universal measure zero ($U_0$) sets (as it is by the presence of large $C$ sets). We also investigate the $\sigma$-ideal $J = \{X \subset \mathbb{R}: X$ cannot be mapped uniformly continuously onto $[0, 1]\}$ and prove various consistency results concerning the relationships between $J$, $U_0$, and AFC (where AFC = $\{X \subset \mathbb{R}: X$ is always first category\}). These latter results partially answer two questions of J. Brown.

0. Introduction

A set $X \subset \mathbb{R}$ has strong measure zero, or property $C$, if for every sequence $\langle \varepsilon_n: n \in \omega \rangle$ of positive reals converging to zero, there is a sequence $\langle I_n: n \in \omega \rangle$ of intervals covering $X$ such that for all $n \in \omega$, the length of $I_n$ is less than $\varepsilon_n$. The Borel Conjecture is the statement

$$C = [\mathbb{R}]^{\omega_1}.$$ 

It is well known that Martin’s Axiom implies the failure of the Borel Conjecture (see [M3]); on the other hand, in [La], Laver builds a model in which the statement holds.

As a natural generalization, we say that the Generalized Borel Conjecture is the statement

$$C = [\mathbb{R}]^{<c}.$$ 

The conjecture fails under MA; the main result of this paper is the construction of a model in which the conjecture holds. We have the following:

0.0 Theorem The Generalized Borel Conjecture is independent of the axioms of set theory.

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The result is somewhat surprising since a parallel conjecture for other well-known \( \sigma \)-ideals is false in ZFC; for example, if we replace \( C \) by the class \( U_0 \) of universal measure zero sets or by the class AFC of always first category sets (defined below), the conjecture is false by Theorem 0.7 and Lemma 0.9 below.

Our model is obtained by forcing with an \( \omega_2 \)-stage countable support mixed iteration of the Infinitely Often Equal Reals (IOER) order (see [M1, §7] and §1 below) and the Sacks order; in [M1], Miller observes that forcing with the IOER order makes the set of ground model reals have strong measure zero; thus, if one forces with an \( \omega_2 \)-stage iteration (from a model of, say, GCH), every set of reals of power \(< c \) has strong measure zero. In [M2], Miller shows that in the iterated Sacks model, every set of reals of power \( c \) can be mapped continuously onto the unit interval \([0, 1]\); as we show below, “continuous” can be replaced by “uniformly continuous”; one then shows—and this is the difficult part—that Miller’s result holds even when the Sacks order is not used on all (but at least stationarily many) of the coordinates of the iteration. (Thus since uniformly continuous images of strong measure zero sets have strong measure zero (see [M3]), no such set has power \( c \) in our model.) In building our model, we noticed that the conditions under which a partial order \( P \) could be used in a mixed iteration with the Sacks order to produce a model of Miller’s result were satisfied by several well-known orders; we have formulated these conditions as axioms for a class of orders we call strongly proper. Since the Sacks order is itself strongly proper, many of the more technical arguments are made more concise by this unified axiomatic approach.

Considering iterations of strongly proper orders also suggests an approach to another interesting problem which arises from a closer analysis of Miller’s result. The question in its most general form is “Which sets of reals can be mapped uniformly continuously onto \([0, 1]\)?” In ZFC, it follows from the Tietze Extension Theorem that every set of reals containing a perfect set has this property. (To see this for unbounded sets of reals, first use a uniformly continuous homeomorphism, such as \( \tan^{-1} \), from \( \mathbb{R} \) onto a bounded open interval.) This result suggests that the interesting answers to the question lie in the realm of totally imperfect sets, i.e., those sets which have no perfect subset; we call this class TI. Diagram 1 describes some of the relationships between many of the better known subclasses of TI.

We now define these classes (for a survey of results, see [Ku, §40; M3, or BrC]). \( X \in L \) if \( X \) is Luzin, i.e., \( X \) is uncountable and \( |X \cap F| \leq \omega \) for every first category set \( F \). \( X \) is concentrated on a set \( D \) if for every open \( U \supseteq D \), \( |X \cap U| \leq \omega \). \( X \in P \) if \( X \) is concentrated on a countable subset of itself. \( X \in \text{con} \) if \( X \) is concentrated on some countable set of reals. \( X \in C'' \) if \( X \) has the Rothberger property, i.e., for every family \( \mathcal{G}_n \) of open covers there is a diagonal sequence \( U_n \in \mathcal{G}_n \) such that \( X \subseteq \bigcup_{n \in \omega} U_n \). \( X \in U_0 \) if \( X \) has universal measure zero, i.e., \( \mu(X) = 0 \) whenever \( \mu \) is the completion of a finite Borel measure which takes singletons to zero. \( X \in (s)_0 \) if for each perfect \( P \subset \mathbb{R} \) there is a perfect \( Q \subset P \) such that \( X \cap Q = \emptyset \). \( X \in \text{count} \) if \( X \) is countable. \( X \in \mathcal{A}^{\leq \kappa} \), where \( \kappa \) is a cardinal, if \( X \subset A \) and \( |X| < \kappa \). \( X \in S \) if \( X \) is Sierpinski, i.e., \( X \) is uncountable and \( |X \cap N| \leq \omega \) whenever \( N \) has Lebesgue measure zero. \( X \in \lambda \) if for all \( D \subset X \), if \( D \) is countable then \( D \) is a \( G_\delta \) relative to \( X \). \( X \in \lambda^\prime \) if for every countable set \( E \in \mathbb{R} \), \( X \cup E \in \lambda \). \( X \in \text{AFC} \) if \( X \) is always first category, i.e., \( X \cap P \) is first category relative to \( P \) for each perfect set \( P \subset \mathbb{R} \). \( X \in \text{AFC} \) (see [G2]) if \( f^{-1}(X) \in \text{AFC} \) whenever \( f \) is 1-1 and continuous.
A class $\mathcal{K} \subset P(\mathbb{R})$ is **hereditary** if $P(Y) \subset \mathcal{K}$ for each $Y \in \mathcal{K}$; $\mathcal{K}$ is a **$\sigma$-ideal** if it is hereditary and closed under countable unions. In Diagram 1, all classes are hereditary except for $L$ and $S$; all are closed under countable unions except $C''$, $\lambda$, and TI.

For sets $X \in \mathbb{R}$ (or occasionally $X \subset Y$, where $Y$ is some compact metric space) we write $M(X)$ if $X$ can be mapped uniformly continuously onto $[0, 1]$. As we observed above, $M(X)$ holds whenever $X \not\in TI$.

In [Is], Isbell improved this result for $X \subset 2^{\omega}$ (where $2^{\omega}$ = the product space of $\omega$ copies of 2 = $\{0, 1\}$; recall that $2^{\omega} \sim$ = the Cantor set) by showing that for all $X \not\in (s)_{0}$, $M(X)$ holds. Let us show why his result holds for $X \subset \mathbb{R}$ as well: Using tan$^{-1}$ as remarked above, we may assume $X \subset [0, 1]$. Let $P \subset [0, 1]$ witness that $X \not\in (s)_{0}$; we may assume $P$ is nowhere dense. Note that $X \cap P \not\in (s)_{0}$ and that by compactness of $P$, any homeomorphism from $P$ onto $2^{\omega}$ is uniformly continuous.

Thus since $M(X \cap P)$ holds, we can find $\hat{\varphi}: P \to [0, 1]$, whence a $\hat{\varphi}': [0, 1] \to [0, 1]$ extending $\varphi$, for which $\varphi''(X \cap P) = \hat{\varphi}''(X \cap P) = [0, 1]$; $\hat{\varphi} \restriction X$ is the required function.

The class of sets satisfying $M$ can be broadened further by observing that there is always an $X \in (s)_{0}$ for which $M(X)$ holds. We need the following proposition:

0.1 **Proposition** If $X$ and $Y$ are compact metric spaces, $f: X \to Y$ is 1-1 and continuous, $S \subset X$, and $f''(S) \in (s)_{0}$ relative to $Y$, then $S \in (s)_{0}$ relative to $X$.

**Proof.** Suppose $P \subset X$ is perfect; since $f''(P)$ is perfect, there is a perfect $Q \subset f''(P)$ missing $f''(S)$; now $f^{-1}(Q)$ misses $S$. □

Now by [W, Theorem 2.2] (see also [M3, 5.10]), there is an $(s)_{0}$ set $S \subset 2^{\omega}$ of power $c$, where $c$ is the cardinality of the continuum. Let $f: S \to 2^{\omega}$ be a bijection and notice that by the proposition $f \subset 2^{\omega} \times 2^{\omega}$ is $(s)_{0}$. Thus if $\pi: 2^{\omega} \times 2^{\omega} \to 2^{\omega}$ is projection onto the second coordinate, $\pi \restriction f$ is a uniformly continuous map from an $(s)_{0}$ set onto $2^{\omega}$. Since the canonical homeomorphism from $2^{\omega}$ onto $2^{\omega} \times 2^{\omega}$ and the usual continuous map from $2^{\omega}$ onto $[0, 1]$ are uniformly continuous, the result follows.

Thus even “fairly small” sets satisfy $M$. However in ZFC one cannot expect to map all $(s)_{0}$ sets of power $c$ uniformly continuously onto $[0, 1]$ because assuming...
CH (or MA) there are Luzin and Sierpinski (c-Luzin and c-Serendip) sets. (Say that \( X \) is \( \kappa \)-Luzin (or \( \kappa \)-Sierpinski) if \( |X| \geq \kappa \) and \( |X \cap F| < \kappa \) whenever \( F \) is first category (or Lebesgue measure zero).) Thus by the following corollary to an observation of Miller, and by the observation that \( \kappa \)-Luzin and \( \kappa \)-Sierpinski sets are \( (s)_0 \), it is consistent that \( M(X) \) fails for some \( X \in (s)_0 \).

0.2 Proposition [M2] No \( \kappa \)-Luzin or \( \kappa \)-Sierpinski set can be mapped continuously onto \([0,1]\).

We now show that every set of reals of power \( c \) satisfies \( M \) in the iterated Sacks model: Miller [M2] actually proves this for \( X \subset 2^\omega \). Suppose \( X \in \mathbb{R} \) and \( X \in (s)_0 \); again assume \( X \) is bounded. Notice that \( |X \cap P| = c \) for some bounded nowhere dense perfect set \( P \) (otherwise \( X \) is c-Luzin and it follows that there is such a set in \( 2^\omega \), contradicting Proposition 0.2). Now map \( X \cap P \) uniformly continuously onto \([0,1]\) using Miller’s result (and a homeomorphism from \( P \) onto \( 2^\omega \)) and extend this map to a \( \varphi : I \rightarrow [0,1] \), where \( I \) is a closed interval containing \( X \cup P \). Now \( \varphi \upharpoonright X \) is the required map.

Hence, Isbell’s result on \( X \notin (s)_0 \) is extended to \( X \notin [\mathbb{R}]^{<c} \) in Miller’s model, and we have the consistency of

\[
(*) \quad \text{Every set of reals of power } c \text{ satisfies } M.
\]

In this model, the \( \sigma \)-ideals more restrictive than \( (s)_0 \) (i.e., \( U_0 \), AFC and their subideals; see Diagram 1) are properly contained in \([\mathbb{R}]^{<c}\). (Laver [La] showed \( U_0 \subset [\mathbb{R}]^{<c} \); Miller [M2] showed \( \text{AFC} \subset [\mathbb{R}]^{<c} \) and it follows from 0.7 and 0.9 below that the inclusions are proper.) It is natural to ask whether \( (*) \) can still hold in a model in which these smaller ideals have members of power \( c \). As Theorem 0.0 shows, it is consistent for every \( X \notin C \) to satisfy \( M \). Moreover, in this model there are many \( U_0 \) sets of power \( c \):

0.3 Theorem If ZFC is consistent, so is ZFC + “Every set of reals of power \( c \) satisfies \( M \) and there are \( 2^c \) sets in \( U_0 \) of power \( c \).

0.4 Remark The situation in the category direction is less clear; the only known “lower bound” for \( (*) \) in this direction is \( S \) (by Proposition 0.2). In particular, it is unknown whether \( (*) \) can hold in a model in which there are AFC sets of power \( c \). A natural strategy to build such a model is to find a strongly proper order \( P \) which forces the ground model reals to be meager. Then by 0.7(b) and 0.9(b) below, there are \( 2^c \) sets in AFC in a model obtained by forcing with \( \omega_2 \)-stage countable support mixed iteration of the Sacks order with \( P \).

It is apparent from Isbell’s result that the sets for which \( M \) fails are “small”; in fact, as we show in §3, if \( J = \{ X \subset \mathbb{R} : \neg M(X) \} \), then \( J \) is a \( \sigma \)-ideal. We have seen that \( C \subseteq J \subseteq (s)_0 \). In light of Diagram 1, it is natural to ask what the relationship is between \( J \) and \( U_0 \) and between \( J \) and AFC. (The relationship between \( J \) and \([\mathbb{R}]^{<c}\) is easily described: clearly \([\mathbb{R}]^{<c} \subseteq J \); CH implies \([\mathbb{R}]^{<c} \neq J \); in Miller’s model described above, \([\mathbb{R}]^{<c} = J \).) Apart from the question of whether “\( J \subseteq \text{AFC} \)” is consistent (which is still open) we give a complete description of these relationships as follows.

0.5 Theorem (a) ZFC + \( U_0 \neq J \) and AFC \( \neq J \);
(b) ZFC + CH + \( U_0 \cap \text{AFC} \subset J \) and \( J \subset U_0 \cup \text{AFC} \);
(c) \( \text{Con}(\text{ZFC}) \rightarrow \text{Con}(\text{ZFC} + U_0 \subseteq J + \text{AFC} \subseteq J) \);
(d) \( \text{Con}(\text{ZFC}) \rightarrow \text{Con}(\text{ZFC} + J \subseteq U_0) \).

Part (d) is established using the model in Theorem 0.0.

As a final application of our techniques, we discuss two problems raised by J. Brown [Brl] (see also [BrC] and [Br2]). The first question is whether there is a ZFC example of a set in \( U_0 \setminus \text{AFC} \) or in \( \text{AFC} \setminus U_0 \). As a partial answer, we prove the following.

0.6 Theorem (a) In the random real model (or if \( c \) is real-valued measurable) we have \( U_0 \subseteq \overline{\text{AFC}} \subseteq \text{AFC} \).
(b) In the Cohen real model, \( \overline{\text{AFC}} \subseteq U_0 \) (in fact, \( \overline{\text{AFC}} \subseteq C'' \)).
(c) \( \text{Con}(\text{ZFC}) \rightarrow \text{Con}(\text{ZFC} + \text{either } \varphi \text{ or } \psi) \) where \( \varphi \equiv \text{"AFC } \not\subseteq U_0 \text{"} \) and \( \psi \equiv \text{"every set of reals of power } c \text{ satisfies } M, \text{ and there are } 2^c \text{ many AFC sets of power } c." \)

Part (b) of the theorem is related to the second question which concerns us. Sierpiński [Si] showed that \( \lambda' \cap \text{con} = \text{count} \). Referring to Diagram 1, one naturally asks whether

\[ \text{(**) } \lambda' \cap C'' = \text{count} \]

is true. Since \( C'' = \text{count} \) is possible (in Laver’s model, see [La]; but note also that \( \lambda' \supseteq \text{count} \) is always true, see [M3]), it is natural to look for a model in which \( C'' \) has uncountable members and (**) fails. As a case of special interest, Brown asks if \( \text{CH } \rightarrow \neg(\text{**}) \). Todorcevic and Miller brought to the author’s attention the fact that a minor modification of Todorcevic’s proof of Theorem 4 in [GM] yields a positive answer to Brown’s question. (In fact, in unpublished work, Todorcevic has constructed an uncountable set in \( \lambda' \cap C'' \) which is also a \( \sigma \) set (i.e. a set whose relative \( F_\sigma \) subsets are relative \( G_\delta \)'s) under the weaker assumption of MA.) Here we wish to observe simply that (**) can fail badly since Theorem 0.6(b) provides a model of \( \lambda' \subset C'' \).

Let \( \mathcal{I} = \{ X \subset \mathbb{R}: X \text{ cannot be mapped continuously onto } [0, 1] \} \). In this paper, we emphasize the study of \( J \) rather than \( \mathcal{I} \) because the former seems to be the more natural of the two classes. For example, while \( J \) is a \( \sigma \)-ideal, whether \( \mathcal{I} \) is also a \( \sigma \)-ideal is independent: in Miller’s model, \( \mathcal{I} = J = [\mathbb{R}]^< \); on the other hand, assuming \( \text{CH} \), there is a scale in \( \omega^\omega \) (recall \( \omega^\omega \cong \{ \text{irrationals} \} \)) which can be mapped continuously onto \( [0, 1] \); however, if \( S \) is any scale and \( Q = \{ \text{rationals} \} \), then \( S \cup Q \in \mathcal{I} \) (see [M3]). Thus \( \mathcal{I} \) is not hereditary under CH. (\( \mathcal{I} \) is closed under countable unions; the argument is the same as that used for \( J \) in §3.) Another undecidable property of \( \mathcal{I} \) is whether \( C \subset \mathcal{I} \): On the one hand, a scale is in \( C \setminus \mathcal{I} \); on the other hand in Laver’s model [La], \( C = \text{count } \subset \mathcal{I} \).

The paper is organized as follows. In §1, we introduce strongly proper orders and discuss their relationship to other well-known classes of orders. In §2 we develop the machinery for iterating these orders, and in §3 we apply this machinery to prove the results stated in this introduction.

We will make liberal use of Cichon’s Diagram [F], which is presented as Diagram
If \( T \subset P(\mathbb{R}) \), \( \text{non}(T) = \min\{|X|: X \not\in T\} \), \( \text{cov}(T) = \min\{|\mathcal{U}|: \mathcal{U} \subset T \text{ and } \bigcup \mathcal{U} = \mathbb{R}\} \), \( \text{add}(T) = \min\{|\mathcal{U}|: \mathcal{U} \subset T \text{ and } \bigcup \mathcal{U} \not\in T\} \), and \( \text{cf}(T) = \min\{|\mathcal{U}|: \mathcal{U} \subset T \text{ and } \bigcup \mathcal{U} \text{ is a member of } \mathcal{U}\} \). Let \( \mathcal{K} \text{ and } \mathcal{L} \) denote the \( \sigma \)-ideals of first category and Lebesgue measure zero sets, respectively. If \( f,g \in \omega^{\omega} \), we write \( f <^* g \) iff there is an \( n \in \omega \) so that for all \( m \geq n \), \( f(m) < g(m) \). Then \( b = \min\{|\mathcal{V}|: \mathcal{V} \subset \omega^{\omega} \text{ and } \mathcal{V} \text{ is } <^*-\text{unbounded}\} \) and \( d = \min\{|\mathcal{V}|: \mathcal{V} \subset \omega^{\omega} \text{ and } \mathcal{V} \text{ is } <^*-\text{cofinal}\} \).

In the diagram, an arrow \( \rightarrow \) indicates that \( \leq \) is provable in ZFC. We state two results which illustrate the connection between these cardinals and the classes we have been considering.

0.7 Theorem \([G1, G2, G3]\) (a) There is a set \( X \in U_0 \) of power \( \text{non}(\mathcal{L}) \).
(b) There is a set \( X \in \overline{\text{AFC}} \) of power \( \text{non}(\mathcal{K}) \).

0.8 Theorem \([FM]\). \( \text{cov}(\mathcal{K}) \leq \text{non}(\mathcal{C}'') \).

In \S3 we prove the following:

0.9 Lemma (a) \( \text{non}(\mathcal{L}) = \text{non}(U_0) \).
(b) \( \text{non}(\mathcal{K}) = \text{non}(\overline{\text{AFC}}) = \text{non}(\text{AFC}) \).

In proving results about relationships between various classes, we often work in \([0,1]\), \( 2^{\omega} \), or \( \omega^{\omega} \) instead of in \( \mathbb{R} \); the fact that there are measure-preserving and category-preserving maps between these spaces (see \([M3]\)) is generally enough to justify this laxity. Whenever these maps do not suffice for the argument at hand (as in some of the arguments above) we supply the necessary additional details in the proof. In particular, in discussing strong measure zero sets, we work only in \( \mathbb{R} \), \([0,1]\) or \( 2^{\omega} \) (see \([Ba, \S9]\)).

In closing this introduction I would like to thank A. W. Miller for several helpful discussions that have resulted in additional applications of the main construction, and A. Kanamori for asking what happens when \( c \) is real-valued measurable. I would also like to thank my thesis committee, Stewart Baldwin, Robert Beaudoin, Jack Brown, Peg Daniels, and Gary Gruenhage, for having listened patiently to several versions of this material.

1. Strongly proper orders

Let \( P \) denote the Sacks order (see \([S \text{ or BL}]\) for definitions and basic results), and for all \( p,p' \in P \) and \( s \in P \) let \( p_s = \{ t \in P: t \supset s \text{ or } s \subset t \} \). For \( m,n \in \omega \) and \( q,p \in P \), write \( (q,m) < (p,n) \) if \( m > n \), \( q \leq p \), and for each \( s \in p \cap 2^n \) there are \( t \neq t' \in q \cap 2^m \) which extend \( s \). It is well known that if \( n \in \omega \) and \( p \vdash \dot{a} \in V \), then there are \( q \in P \), \( m \in \omega \) and \( x_s \in V \) for each \( s \in q \cap 2^n \) such that \( (q,m) < (p,n) \) and...
and \( q_s \models \dot{a} = x_s \); moreover, since the set \( \{ q_s : s \in q \cap 2^n \} \) is a maximal antichain below \( q \), it follows that \( q \models \dot{a} \in \{ x_s : s \in q \cap 2^n \} \).

The properties described above are to a large extent preserved by countable support iterations of the Sacks order, and Miller’s consistency result [M2] relies heavily on this fact. Since several well-known partial orders have these properties, and since much of Miller’s machinery goes through for any such partial order, we have formulated the properties as axioms for a class of orders which we will call strongly proper. Ultimately, we will use a particular strongly proper order along with the Sacks order in a countable support iteration to obtain most of the results discussed in §0.

1.0 Definition (strongly proper orders) A partial order \( (P, \leq) \) is strongly proper if there are orderings \( \{ <_{m,n} : n < m \in \omega \} \) and a constructible sequence \( T = \langle T_n : n \in \omega \rangle \) of finite sets satisfying:

1. \( T_0 = \{ \emptyset \} \).

2. If \( q <_{m,n} p \) (which we will write \( (q,m) < (p,n) \)), then \( m > n, q \leq p \), and whenever \( m' \geq m \) and \( n' \leq n \) then \( (q,m') < (p,n') \).

3. (Fusion) If \( \{ (p_n, m_n) : n \in \omega \} \) is a sequence such that for all \( n \in \omega \), \( (p_{n+1}, m_{n+1}) < (p_n, m_n) \), there is a \( p \in P \) such that for all \( n \in \omega \), \( (p, m_{n+1}) < (p_n, m_n) \). Such a sequence will be called a fusion sequence and the condition \( p \) will be called a fusion of this sequence.

4. For each \( p \in P, n \in \omega \), there is a nonempty \( A_{p,n} \subset T_n \) and a map \( \varphi_{p,n} : A_{p,n} \to P \) (whose images \( \varphi_{p,n}(s) \) we denote by \( p_s \) whenever \( n \) is fixed) such that
   \( a \) \( \varphi_{p,0}(s) = p ; \)
   \( b \) the set \( \{ p_s : s \in A_{p,n} \} \) is a maximal antichain below \( p ; \)
   \( c \) \( \forall p, q \in P[ (q,m) < (p,n) \to A_{q,n} = A_{p,n} ; \)
   \( d \) \( \forall p, q, r \in P[ (q,m) < (p,n) \land q \leq p \land A_{q,n} = A_{p,n} \to (r,m) < (p,n) ] ; \)
   \( e \) \( \text{If } p \models "\dot{a} \in V^n \text{ and } n \in \omega \text{, then there are } m > n \text{ and } q \in P \text{ such that } (q,m) < (p,n) \text{ and for each } s \in A_{q,n} \text{ there is an } x_s \in V \text{ so that } q_s \models \dot{a} = x_s. \)

1.1 Notation. For \( p, q \in P \) and \( n \in \omega \) we write \( (q,n) \leq (p,n) \text{ if } q \leq p \text{ and } A_{q,n} = A_{p,n} \).

Miller points out that much of the strength of these axioms is embodied in the notion of \( \omega^\omega \)-bounding orders, discussed by Shelah in [Sh]. (A partial order \( Q \) is \( \omega^\omega \)-bounding if for each \( f \in V^Q \) for which \( \models Q \f : \omega \to \omega \), there is \( g \in V, g : \omega \to \omega \), such that \( \models Q \forall n \dot{f}(n) \leq g(n) \); note that strongly proper orders have this property by Axioms 3, 4(e).) Shelah [Sh, p. 169] shows that “\( \omega \)-proper + \( \omega^\omega \)-bounding” is preserved by countable support iterations. One might hope to replace our somewhat lengthy list of axioms with this more concise list of two. In §2, however, we show that our central lemma (Theorem 2.23) fails if “strongly proper” is replaced by “\( \omega \)-proper + \( \omega^\omega \)-bounding” (see Remark 2.24).

We now briefly examine the relationship between strongly proper orders and other well-known classes of orders. We show that the strongly proper orders are properly included in the class of \( \omega \)-proper, \( \omega^\omega \)-bounding orders and that \( \omega_1 \)-closed
orders are strongly proper, as are several other familiar orders. We first show the following:

1.2 Theorem Strongly proper orders do not add Cohen or random reals.

Proof. That Cohen reals are not added follows from the \( \omega^\omega \)-bounding property: If \( \dot{x} \in V^P \), \( \| p \| \dot{x} \in \omega^\omega \), and \( f : \omega \to \omega \) in \( V \) with \( \| p \| \forall n (\dot{x}(n) \leq f(n)) \) then the set \( \{ g \in \omega^\omega | \forall n (g(n) \leq f(n)) \} \) is nowhere dense, coded in \( V \), and contains \( \dot{x} \).

That random reals are not added follows from Remark 2.23; we give a direct proof which does not involve the machinery of iterations in an essential way.

**Lemma** If \( P \) is strongly proper, \( p \in P \), \( p \vdash \dot{a} \notin V \) and \( \dot{a} \in 2^{\omega} \), and \( n \in \omega \), then there is a finite \( X \in V \) and a \( q \in P \) such that \( (q, n) \leq (p, n) \) and

\[
q \vdash \exists x \in X [x \upharpoonright 2(|X| + n) = \dot{a} \upharpoonright 2(|X| + n)].
\]

Proof. We postpone the proof to §2 where we prove a much more general statement (see Lemma 2.15).

**Lemma** If \( P \) is strongly proper, \( p \in P \), and \( p \vdash \dot{a} \notin V \) and \( \dot{a} \in 2^{\omega} \), then there is a sequence \( \langle X_n : n \in \omega \rangle \in V \) of finite sets and a condition \( q \leq p \) so that for all \( n \in \omega \),

\[
q \vdash \exists x \in X_n [x \upharpoonright 2(|X_n| + n) = \dot{a} \upharpoonright 2(|X_n| + n)].
\]

Proof. We use fusion and Axiom 4(e). By induction, build a fusion sequence \( \{ (p_n, m_n) : n \in \omega \} \) and a sequence \( \langle X_n : n \in \omega \rangle \) of finite sets so that

1. \( p_0 = p \) and \( m_0 \) is arbitrary;
2. \( p_{n+1} \vdash \exists x \in X_n [x \upharpoonright 2(|X_n| + n) = \dot{a} \upharpoonright 2(|X_n| + n)] \).

If \( (p_n, m_n) \) have been defined, let \( (r, m_n) \leq (p_n, m_n) \) and \( X_n \) be as in the first lemma, and let \( (p_{n+1}, m_{n+1}) < (r, m_n) \) be as in Axiom 4(e). Now by Axiom 4(d), \( (p_{n+1}, m_{n+1}) < (p_n, m_n) \), and the induction is complete. Clearly, if \( q \) is a fusion of the \( (p_n, m_n) \), \( q \) satisfies the conclusion of the lemma.

We now finish the proof of Theorem 1.2. Suppose \( p \vdash \dot{a} \notin V \) and \( \dot{a} \in 2^{\omega} \). Let \( q \leq p \) and \( \langle X_n : n \in \omega \rangle \) be as in the second lemma. Then if \( q \in G \), \( G P \)-generic over \( V \), then in \( V[G] \) the set

\[
\bigcap_n \bigcup_x \{ f \in 2^\omega : f \upharpoonright 2(|X_n| + n) = x \upharpoonright 2(|X_n| + n) \}
\]

is coded in \( V \), contains \( \dot{a} \), and has measure zero. (To see the last part, notice that before taking the intersection, the \( n \)th union has measure \( \leq 1/2^{2(|X_n| + n)} \).)

1.3 Corollary The class of strongly proper orders is properly included in the class of \( \omega \)-proper, \( \omega^\omega \)-bounding orders.

Proof. Because of our earlier remarks, to prove inclusion we have only to prove that strongly proper orders are \( \omega \)-proper; the proof of the latter is a straightforward
modification of the argument that Axiom A orders are proper (using the model-theoretic definition of proper) (see [Sh, p. 169] for definitions).

To see that inclusion is proper, we show that the random real order is ω-proper and ω-range-bounding (we have already seen it is not strongly proper): Being ccc, it is ω-proper; that it is also ω-range-bounding is folklore (see [J2, p. 14] for a proof). □

1.4 Remark The similarity between strongly proper orders and Axiom A orders is evident; 1.2 shows the classes are different and suggests the following questions.

1.5 Questions. (i) Does every strongly proper order satisfy Axiom A?
   (ii) Is there a nonatomic ccc order which is strongly proper?

We proceed to several examples.

1.6 Proposition The Sacks order is strongly proper.

Proof. Define $T_n, A_{p,n}, \varphi_{p,n}$, and $<_{m,n}$ as follows: $T_n = 2^n$; $A_{p,n} = p \cap 2^n$; $\varphi_{p,n}(s) = p_s$; and $(q, m) < (p, n)$ is defined as in the first paragraph of this section. □

1.7 Remark One reason we opted for the $<_{m,n}$ orderings rather than the simpler Axiom A orderings $\leq_n$ is that the analogue to Axiom 4(e) fails for the Sacks order if the usual $\leq_n$ orderings are used in place of the $<_{m,n}$ (see [Ba, §7] for definitions and results).

1.8 Proposition Each $\omega_1$-closed order is strongly proper.

Proof. Let $T_n = A_{p,n} = \{\emptyset\}$, $\varphi_{p,n}(\emptyset) = p$, and let $<_{m,n}$ be $\leq$. □

1.9 Definition Let $P = \{p: A \to 2^{<\omega} | A \subseteq \omega \text{ is coinfinite and for all } n \in A, p(n) \in 2^n\}$ and write $q \leq p$ if $q \supseteq p$. $P$ is called the Infinitely Often Equal Reals (IOER) order (see [M1, §7]).

1.10 Proposition The IOER order is strongly proper.

Proof. We define $T_n, A_{p,n}, \varphi_{p,n}$, and $<_{m,n}$ as follows:

$$T_n = \{s: s \text{ is a partial function from } n \text{ into } 2^{<n} \text{ such that for all } i \in \text{dom } s, s(i) \in 2^i\};$$

$$A_{p,n} = \{s \in T_n: \text{dom } s = n \setminus \text{dom } p\};$$

$$\varphi_{p,n}(s) = p \cup s;$$

$$(q, m) < (p, n) \text{ if } m > n, q \leq p, A_{p,n} = A_{q,n}, \text{ and there is } i, n < i \leq m, \text{ such that } i \notin \text{dom } q.$$}

We verify that Axioms 4(b) and 4(e) hold; the others are immediate.

It is clear that the set $\{p \cup s: s \in A_{p,n}\}$ is an antichain; if $q \leq p$, then $q$ must agree with some $s \in A_{p,n}$ on their common domain; thus the set is in fact maximal below $p$.

For 4(e), assume $p \Vdash "\dot{a} \in V", n \in \omega$. Write $A_{p,n} = \{s_1, \ldots, s_k\}$. Build $(q, n) \geq (q_2, n) \geq \cdots \geq (q_k, n)$ and $\{x_1, \ldots, x_k\} \subseteq V$ so that for $1 \leq i \leq k$, $q_i \cup s_i \Vdash \dot{a} = x_i$. Given $q_i$, obtain $q' \leq q_i \cup s_{i+1}$ and $x_{i+1} \in V$ so that $q' \Vdash \dot{a} = x_{i+1}$. Let $q_{i+1} = q' \setminus s_{i+1}$. Now let $q = q_k$ and let $m$ be large enough so that $(q, m) < (q, n)$. Then $(q, m)$ is the required pair. □
1.11 Remark (i) The verification of 4(e) above is a minor modification of a similar proof by Miller [M1, §7].
(ii) Let $P = \{ p : A \rightarrow 2 | A \subset \omega \text{ is cofinite} \}$ and say $q \leq p$ if $q \supset p$. $P$ is Silver forcing and an argument similar to the one given above shows that $P$ is strongly proper.

2. Iterations

In this section we develop the machinery for iterating strongly proper orders. Our notation and terminology for general iterated forcing follow [Ba]; our arguments are patterned after [BL] and [M2]. Recall that if $P_\alpha$ is an $\alpha$-stage iteration and $p \in P_\alpha$, then for all $\beta < \alpha$, $p \upharpoonright \beta \in P_\beta$ and $\forces_{\beta} p(\beta) \in Q_\beta$. However, if we need to verify that a particular $p$ (having the right kind of support) is in $P_\alpha$, it suffices to check that for all $\beta < \alpha$, $p \upharpoonright \beta \in P_\beta$ and $p \upharpoonright \beta \forces_{\beta} p(\beta) \in Q_\beta$ (see [Ba]); we use this fact without special mention.

For the rest of this section, $P_\alpha$ will denote a countable support $\alpha$-stage iteration and for all $\beta < \alpha$, $T^\beta = \{ T_n^\beta : n \in \omega \}$ is a constructible set of finite sets, and $\{ A^\beta_{\tau,n} : n \in \omega \text{ and } \forces_{\beta} \tau \in Q_\beta \}$, $\{ \varphi^\beta_{\tau,n} : n \in \omega \text{ and } \forces_{\beta} \tau \in Q_\beta \}$ are sets of terms such that

$$\forces_{\beta} "T^\beta, \{ A^\beta_{\tau,n} \}_{\tau,n}, \{ \varphi^\beta_{\tau,n} \}_{\tau,n} \text{ witness that } Q_\beta \text{ is strongly proper}".$$

In practice, the fact that we use only canonical terms for the $T^\beta$ is not a restriction at all since in any application of such an iteration, we would have a particular (constructible) definition of $T^\beta$ in mind for each factor $Q_\beta$ (and canonical names would be perfectly general). (Of course for a general theory of iterated strongly proper orders, arbitrary terms for the $T^\beta$ would have to be allowed.)

2.0 Definition If $F \in [\alpha]^{< \omega}$ and $n < m \in \omega$, then $(q, m) <_F (p, n)$ if $q \leq p$, $m > n$, and $q \upharpoonright \beta \forces "(q(\beta), m) < (p(\beta), n)"$ for all $\beta \in F$.

2.1 Lemma (Fusion). Suppose $\{ (p_n, F_n, m_n) : n \in \omega \}$ is a sequence such that for all $n$, $p_n \in P_{\alpha}$, $F_n \in [\alpha]^{< \omega}$, $(p_{n+1}, m_{n+1}) <_{F_n} (p_n, m_n)$, $F_n \subset F_{n+1}$ and $\bigcup_n F_n = \bigcup_n \text{suppt} (p_n)$. Then there is $p \in P_{\alpha}$ such that for all $n$, $(p, m_{n+1}) <_{F_n} (p_n, m_n)$.

Proof. Define $p \upharpoonright \beta$ by induction on $\beta \leq \alpha$ so that for all $n$, $(p \upharpoonright \beta, m_{n+1}) <_{F_n} (p_n \upharpoonright \beta, m_n)$ and $\text{suppt} (p \upharpoonright \beta) = (\bigcup_n F_n) \cap \beta$. If $\beta$ is a limit, take the union of the restrictions defined below $\beta$. To obtain $p \upharpoonright \beta + 1$ from $p \upharpoonright \beta$ where $\beta < \alpha$, let $p(\beta) = 1$ if $\beta \notin \bigcup_n F_n$; if $\beta \in \bigcup_n F_n$, use the fact $p \upharpoonright \beta$ forces Axiom (4) to hold for $Q_\beta$ to obtain $p(\beta)$ as follows: Let $n$ be least such that $\beta \in F_n$. For $k \in \omega$, let $q_k = Q_{n+k}(\beta)$ and let $j_k = m_{n+k}$. Now

$$p \upharpoonright \beta \forces "<(q_k, j_k) : k \in \omega \text{ is a fusion sequence}".$$

Let $p(\beta)$ be a term forced by $p \upharpoonright \beta$ to be the fusion of the $(q_k, j_k)$. To complete the proof it suffices to verify that $(p \upharpoonright \beta + 1, m_{i+1}) <_{F_i} (p_i \upharpoonright \beta + 1, m_i)$ for all $i \in \omega$. For $i \geq n$, this follows from the definition of $p(\beta)$; as a consequence we have that

$$\forall i \in \omega (p \upharpoonright \beta + 1 \leq p_i \upharpoonright \beta + 1)$$
From this and the induction hypothesis we have the result for $i < n$ as well. □

2.2 Remark The sequence $\{(p_n, F_n, m_n): n \in \omega\}$ will be called a fusion sequence and the condition $p$ constructed above will be called a fusion of $\{(p_n, F_n, m_n): n \in \omega\}$.

2.3 Definition For $F \in [\alpha]^{<\omega}$, $n \in \omega$, a function $\sigma$ on $F$ is called an $(F, n)$-function if for all $\beta \in F$, $\sigma(\beta) \in T^\beta_n$. If $\sigma$ is an $(F, n)$-function define $p[\sigma]$ by

$$p[\sigma](\beta) = \begin{cases} p(\beta) & \text{if } \beta \notin F, \\ \varphi^\beta_{p(\beta), n}(\sigma(\nu)) & \text{if } \beta \in F. \end{cases}$$

(In other words, if $\beta \in F$, $p[\sigma](\beta) = p(\beta)_{\sigma(\beta)}$.)

Notice that, in general, $p[\sigma]$ need not be in $P_\alpha$.

2.4 Definition A function $\sigma$ on $F$ is $(F, n)$-consistent with $p$ if $\sigma$ is an $(F, n)$-function and, for all $\beta \in F$,

$$(p[\sigma] \upharpoonright \beta) \models \sigma(\beta) \in \hat{A}^\beta_{p(\beta), n}.$$ 

(In other words, modulo our convention, $p[\sigma] \in P_\alpha$.)

2.5 Definition The condition $p \in P_\alpha$ is $(F, n)$-determined if for each $(F, n)$-function $\sigma$, either $\sigma$ is $(F, n)$-consistent with $p$ or

$$\exists \beta \in F(\sigma \upharpoonright F \cap \beta \text{ is } (F \cap \beta, n)-\text{consistent with } p \upharpoonright \beta$$

and $(p[\sigma] \upharpoonright \beta) \nvdash "\sigma(\beta) \notin \hat{A}^\beta_{p(\beta), n}"$.

2.6 Notation. We write $\Sigma(p, F, n)$ for the set $\{\sigma: \sigma \text{ is } (F, n)-\text{consistent with } p\}$.

2.7 Definition If $p, q \in P_\alpha$, $n \in \omega$, $F \in [\alpha]^{<\omega}$, then $(q, n) \leq_F (p, n)$ if $q \leq p$ and $q \upharpoonright \beta \models (q(\beta), n) \leq (p(\beta), n)$ for all $\beta \in F$.

2.8 Proposition (i) If $(q, m) \prec_F (p, n)$, $m' \geq m$, $n' \leq n$, then $(q, m') \prec_F (p, n')$.

(ii) If $(q, m) \prec_F (p, n)$, then $(q, n) \leq_F (p, n)$.

(iii) If $(r, m) \prec_F (q, n)$ and $(q, n) \leq_F (p, n)$, then $(r, m) \prec_F (p, n)$.

(iv) If $\sigma \neq \tau$ are in $\Sigma(p, F, n)$, then $p[\sigma] \not\perp p[\tau]$.

Proof. Proceed by induction on $\beta \in F$; for (i) use Axiom (2); for (ii) use Axiom 4(c); for (iii) use Axiom 4(d); and for (iv) use Axiom 4(b). □

2.9 Lemma For all $p \in P_\alpha$, if $p$ is $(F, n)$-determined, $\{p[\sigma]: \sigma \in \Sigma(p, F, n)\}$ is a maximal antichain below $p$.

Proof. By 2.8, it suffices to prove maximality. Suppose $q \leq p$. By induction on $\beta \leq \alpha$ we find $q \upharpoonright \beta, \sigma \upharpoonright F \cap \beta$, and $r \upharpoonright \beta$ so that $r \upharpoonright \beta \leq q \upharpoonright \beta$, $(p[\sigma] \upharpoonright F \cap \beta) \models \beta$. The cases in which $\beta$ is a limit and $\beta = \gamma + 1$ with $\gamma \notin F$ are easy. We assume $\beta = \gamma + 1$ and $\gamma \in F$. Assuming $r \upharpoonright \gamma, \sigma \upharpoonright F \cap \gamma$, and $q \upharpoonright \gamma$ have been defined, it follows from 4(b) that there is a term $\hat{s}$ such that

$$(\ast) \quad r \upharpoonright \gamma \models "\hat{s} \in \hat{A}^\gamma_{p(\gamma), n} \text{ and } p(\gamma)\hat{s} \text{ is compatible with } q(\gamma)\".$$
Let \( r' \leq r \upharpoonright \gamma \) and \( s \in T_\alpha^\nu \) be such that \( r' \models s = \delta \), and let \( \sigma(\gamma) = s \).

**Claim.** \( \sigma \upharpoonright F \cap \beta \) is \((F \cap \beta, n)\)-consistent with \( p \).

**Proof of Claim.** If \( p \models \sigma \upharpoonright \gamma \not\models \sigma(\gamma) = \delta \), then by \((F,n)\)-determinedness of \( p \), \( \sigma(\gamma) \not\in A_{\nu(\gamma),n}^{\beta} \) is forced by \( p \models \gamma \), and hence by \( r' \). But this contradicts \((*)\), and the claim is proven.

Again by \((*)\) we can find a term \( r(\gamma) \) such that \( r' \models r(\gamma) \leq q(\gamma), p(\gamma)_{\sigma(\gamma)} \) (note that \( r' \models \sigma(\gamma) \in A_{\nu(\gamma),n}^{\beta} \)). This completes the induction step and the proof of Lemma 2.9. □

2.10 **Lemma** If \( p \) is \((F,n)\)-determined and \((q,n) \leq_F (p,n) \), then \( q \) is \((F,n)\)-determined.

**Proof.** Suppose \( \sigma \) is \((F,n)\)-consistent with \( q \). First observe that \( \sigma \) is \((F,n)\)-consistent with \( p \) as well: if not, let \( \beta < \alpha \) be least for which this is false, i.e.,

\[
p \models \sigma \upharpoonright \beta \not\models \sigma(\beta) \in A_{\nu(\beta),n}^{\beta}.
\]

By \((F,n)\)-determinedness of \( p \) and the fact that \( q \leq p \) we have

\[
q \models \sigma \upharpoonright \beta \not\models \sigma(\beta) \in A_{\nu(\beta),n}^{\beta}.
\]

But since

\[
(**) \quad q \models \beta \models A_{\nu(\beta),n}^{\beta} = A_{\nu(\beta),n}^{\beta},
\]

we get the contradiction

\[
q \models \beta \not\models \sigma(\beta) \in A_{\nu(\beta),n}^{\beta}.
\]

Now to prove the lemma, let \( \sigma \) be an \((F,n)\)-function and let \( \beta \) be least in \( F \) such that

\[
q \models \beta \not\models \sigma(\beta) \in A_{\nu(\beta),n}^{\beta}.
\]

Use \((**)\) again, the fact that \( q \leq p \), and the observation above to get

\[
p \models \sigma \upharpoonright \beta \not\models \sigma(\beta) \in A_{\nu(\beta),n}^{\beta}.
\]

Now \((**)\) and \((F,n)\)-determinedness of \( p \) give us

\[
q \models \beta \leq p \models \beta \models \sigma(\beta) \not\in A_{\nu(\beta),n}^{\beta} = A_{\nu(\beta),n}^{\beta},
\]

as required. □

2.11 **Lemma** If \( p \) is \((F,n)\)-determined and \((q,n) \leq_F (p,n) \), then \( \Sigma(q,F,n) = \Sigma(p,F,n) \).

**Proof.** The proof of Lemma 2.10 shows that \( \Sigma(q,F,n) \leq \Sigma(p,F,n) \). To get inclusion in the other direction, use \((F,n)\)-determinedness of \( q \). □
The next theorem is the analogue to Axiom 4(e); most of our machinery has been set up to make this theorem true. We include parts (ii) and (iii) in order to make the induction work; they are (essentially) true for any proper order.

2.12 Theorem (i) If \( p \in P_\alpha, \ F \in [\alpha]^<\omega, \ n \in \omega, \) and \( p \models \dot{a} \in V, \) then there are \( q, m \) and, for each \( \sigma \in \Sigma(q,F,n), \) a set \( x_\sigma \in V \) such that \( (q,m) <_F (p,n), \) \( q \) is \((F,n)\)-determined, and for each \( \sigma \in \Sigma(q,F,n), \)

\[
q|\sigma \models \dot{a} = x_\sigma.
\]

Moreover, if \( x = \{ x_\sigma : \sigma \in \Sigma(q,F,n) \}, \) then

\[
q \models \dot{a} \in x.
\]

(ii) If \( p \in P_\alpha, \ F \in [\alpha]^<\omega, \ n \in \omega, \) and \( p \models \text{“} \dot{A} \subset V \land \dot{A} \text{ is countable”,} \) then there are \( q, m, \) and a countable set \( B \in V \) such that \( (q,m) <_F (p,n) \) and \( q \models \dot{A} \subset B. \)

(iii) If \( p \in P_\alpha, \ F \in [\alpha]^<\omega, \ n \in \omega, \) and \( p \models f \in P_{\alpha \gamma}, \) then there are \( q, m, \) and \( g \in P_{\alpha \gamma}, \) such that \( (q,m) <_F (p,n) \) and \( q \models f = g. \)

Proof. We prove (i), (ii) and (iii) simultaneously by induction on \( \alpha. \) Assume the result holds for all \( \beta < \alpha. \)

(i) Case \( \alpha = \beta + 1 \) and \( \beta \in F. \)

Since \( p \models \beta \models p(\beta) \models \dot{a} \in V, \) applying Axiom 4(e) in \( \dot{Q}_\beta, \) we obtain terms \( \dot{m}, \dot{r}, \)

and for each \( s \in T^\beta_\alpha, \dot{x}_s \) such that

\[
p \models \beta \models \forall s \in T^\beta_\alpha[\dot{x}_s \in V \land (s \in A^\beta_{p(\beta)}, n \rightarrow \dot{r} \models \dot{a} = \dot{x}_s) \land (\dot{r}, \dot{m}) < (p(\beta), n)]^
\]

Since

\[
p \models \beta \models (\dot{m}, A^\beta_{p(\beta)}, (\dot{x}_s : s \in T^\beta_\alpha)) \in V,
\]

by the induction hypothesis there are \( q', m_0, \) and for each \( \sigma \in \Sigma(q', F \cap \beta, n), \) sets \( (m_\sigma, \beta_\sigma, (x_\sigma)_s : s \in T^\beta_\alpha')) \in V \) such that \( (q', m_0) <_{F \cap \beta} (p \models \beta, n), \) \( q' \) is \((F \cap \beta, n)\)-determined for each \( \sigma \in \Sigma(q', F \cap \beta, n), \) and, for all \( s \in T^\beta_\alpha, \)

\[
q'|\sigma \models \text{“} \dot{m} = m_\sigma, A^\beta_{p(\beta)} = B_\sigma, \text{ and } \dot{x}_s = x_\sigma; \text{”}
\]

moreover, if \( m_1 = \max\{ m_\sigma : \sigma \in \Sigma(q', F \cap \beta, n) \}, \) then

\[
q' \models \dot{m} \leq m_1.
\]

Now let \( m = \max\{ m_0, m_1 \} \) and let \( q = q' \cup \dot{r}. \)

Claim 1. \( (q, m) <_F (p,n). \)

Proof. \( (q \models \beta, m) <_{F \cap \beta} (p \models \beta, n) \) by Proposition 2.8(i); that \( q \models \beta \models (q(\beta), m) < (p(\beta), n) \) follows from (1) and (2).

Claim 2. \( q \) is \((F,n)\)-determined.
\textbf{Proof.} By the induction hypothesis, it suffices to consider the case in which \( \tau \) is an \((F,n)\)-function, \( \sigma = \tau \restriction F \cap \beta \), \( s = \tau(\beta) \), and \( q[\sigma \restriction \beta] \not\models s \in \hat{A}_{q(\beta),n}^\beta \). We have the following implications:

\[
q[\sigma \restriction \beta] \models \hat{A}_{q(\beta),n}^\beta = B_\sigma \Rightarrow q[\sigma \restriction \beta] \models s \in B_\sigma \Rightarrow s \not\in B_\sigma \Rightarrow q[\sigma \restriction \beta] \not\models s \in \hat{A}_{q(\beta),n}^\beta.
\]

\textbf{Claim 3.} For each \( \tau \in \Sigma(q,F,n) \), there is \( x_\tau \in V \) such that \( q \models \dot{a} = x_\tau \); moreover, if \( x = \{x_\tau : \tau \in \Sigma(q,F,n)\} \), then \( q \models \dot{a} \in x \).

\textbf{Proof.} The second clause follows from the first because of Lemma 2.9. Let \( \sigma = \tau \restriction \beta \) and \( s = \tau(\beta) \). Then

\[
q \restriction \beta \models "p(\beta) \models \dot{a} = x_s \land (1 \models \dot{x}_s = x_{\sigma \restriction s})".
\]

\textbf{Case 2.} \( \alpha \) is a limit or \( \alpha = \beta + 1 \) where \( \beta \not\in F \). In case \( \alpha \) is a limit, choose \( \beta \) so that \( \max F < \beta < \alpha \). Then

\[
p \restriction \beta \models p^\beta \models \dot{a} \in V.
\]

Let \( \dot{f}, \dot{b} \in V^{P_\alpha} \) be such that

\[
p \restriction \beta \models "\dot{f} \leq p^\beta, \dot{b} \in V, \text{ and } \dot{f} \models \dot{a} = \dot{b}".
\]

Use the induction hypothesis to obtain \( q_1 \) and \( m_1 \) such that \( (q_1,m_1) \prec_{F \cap \beta} (p \restriction \beta, n) \), \( q_1 \) is \((F \cap \beta,n)\)-determined, and for each \( \sigma \in \Sigma(q_1,F \cap \beta,n) \) there is \( x_\sigma \in V \) such that

\[
q_1[\sigma] \models \dot{b} = x_\sigma.
\]

By 2.8(ii), \( (q,n) \leq_{F \cap \beta} (p \restriction \beta, n) \); use part (iii) of the induction hypothesis to obtain \( q_2, m_2 \), and \( g \in P_\beta \alpha \) so that \( (q_2,m_2) \prec_{F \cap \beta} (q_1,n) \) and

\[
q_2 \models \dot{f} = g.
\]

Note that by 2.8(ii) and 2.10, \( q_2 \) is \((F \cap \beta,n)\)-determined.

Now, using the fact that \( F \subset \beta \), one easily shows that \( (q_2,g,m) \) is the required pair.

(ii) Let \( p,F,n \), and \( \hat{A} \) be as in the hypothesis and let \( \dot{f} \in V^{P_\alpha} \) be such that \( p \models "\dot{f} : \omega \rightarrow \hat{A} \text{ is a bijection}" \). Obtain a fusion sequence \( \{(q_n,F_n,m_n) : n \in \omega\} \) and a sequence \( \{x_n : n \in \omega\} \) of finite sets so that \( q_0 = p \) and \( q_{n+1} \models \dot{f}(n) \in x_n \). Now let \( B = \bigcup_n x_n \) and let \( q \) be the fusion of the \( (q_n,F_n,m_n) \).

(iii) Given \( \gamma > \alpha, p,F,n \), and \( \dot{f} \) with \( p \models \gamma \dot{f} \in P_{\alpha \gamma} \), let \( q,m,B \) be such that \( B \in V \) is countable, \( (q,m) \prec_F (p,n) \) and \( q \models \operatorname{supp} \dot{f} \subset B \). For each \( \mu \in B \), notice that \( p \) forces \( \dot{f}(\mu) \) to be a term in the language of forcing over \( V \). Thus we let \( g(\mu) \) be such a term denoting the same object in \( V[G_\mu] \) (where \( q \in G_\mu \restriction \alpha \)) as \( \dot{f}(\mu) \).
denotes in $V[G_\alpha][G_\alpha]$ (where $q \in G_\alpha$). Now $g \in P_{\alpha \gamma}$ and $q \Vdash \hat{f} = g$. (See [Ba, §7]
for a similar argument.) \hfill \Box

2.13 **Corollary** $P_\alpha$ does not collapse $\omega_1$. \hfill \Box

As a further application which we will use later in the proof of Theorem 2.22, we show the following:

2.14 **Lemma** Suppose $\text{cf}(\alpha) = \omega_1$ and $G_\alpha$ is $P_\alpha$-generic over $V$. Then for every $f \in V[G_\alpha] \cap 2^\omega$, there is $\beta < \alpha$ such that $f \in V[G_\beta]$.

**Proof.** Let $p \Vdash \hat{f}: \omega \to 2$ and define

\[
\text{a fusion sequence } \{ (q_n, F_n, m_n) : n \in \omega \} \text{ so that } q_0 = p, q_{n+1} = (F_n, m_n)-determined \text{ for all } n \in \omega, \text{ and for all } \sigma \in \Sigma(q_{n+1}, F_n, m_n), \]

\[
q_{n+1}[\sigma] \Vdash \hat{f}(n) = x_\sigma.
\]

Let $q$ be a fusion of the $q_n$ and let $\beta$ be such that $\sup(\text{suppt } q) < \beta < \alpha$. Now if $q \not\Vdash \beta \in G_\beta$, define $g \in \omega^2 \cap V[G_\beta]$ by

\[
g(n) = x_\sigma \text{ iff } \sigma \text{ is the unique member of } \Sigma(q \upharpoonright \beta, F_n, m_n) \text{ for which } (q|\sigma) \Vdash \beta \in G_\beta.
\]

Notice $g$ is well defined because

\[
\Sigma(q \upharpoonright \beta, F_n, m_n) = \Sigma(q_n, F_n, m_n) = \Sigma(q_{n+1}, F_n, m_n).
\]

Thus $q \Vdash \omega \in V[G_\beta] \land \hat{f} = \hat{g}$, as required. \hfill \Box

As a final technical lemma, we show that arbitrarily large initial segments of a new real are determined by a finite set of old reals.

2.15 **Lemma** If $p \Vdash \omega \not\subseteq V$ and $\dot{a} \in 2^\omega$, $n \in \omega$, $F \in [\alpha]^{<\omega}$, $Y \in [2^\omega]^{<\omega} \cap V$ and $p$ is $(F, n)$-determined, there are $X \in [2^\omega]^{<\omega} \cap V$ and for each $k < \omega$ a condition $q^k$

\[
such that
\]

(a) $(q^k, n) \leq_F (p, n)$;

(b) $q^k$ is $(F, n)$-determined;

(c) $q^k \Vdash \exists x \in X(x \upharpoonright k = \dot{a} \upharpoonright k)$; and

(d) $X \cap Y = \emptyset$.

**Proof.** List $\Sigma(p, F, n)$ as $\{ \sigma_0, \sigma_1, \ldots, \sigma_{N-1} \}$. We build a sequence of terms $\langle \dot{s}_i : i \in \omega \rangle$ and conditions $\langle q_i : i \in \omega \rangle$ and an $\omega \times N$ matrix $\langle t_{ij} \rangle$ so that for all $i \in \omega, j \in N$,

\[
(1) q_i|\sigma_j \Vdash \text{"} t_{ij} = \dot{s}_i, \dot{s}_i \text{ is an initial segment of } \dot{a}, \text{ and } \forall y \in Y(y \supset \dot{s}_i)";
\]

\[
(2) (q_{i+1}, n) \leq_F (q_i, n);
\]

\[
(3) q_i \text{ is } (F, n)-determined.
\]

To get the 0th row, note there is a term $\dot{s}_0$ such that

\[
p \Vdash \text{"} \dot{s}_0 \text{ is an initial segment of } \dot{a} \text{ and } \forall y \in Y(y \supset \dot{s}_0)".
\]

Use Theorem 2.12 to obtain $q_0, m_0$, and $t_{0j}, j < N$, so that $(q_0, m_0) \not<_F (p, n)$ (whence $(q_0, n) \leq_F (p, n)$) and for all $j < N$, $q_0|\sigma_j \Vdash \dot{s}_0 = t_{0j}$. Note that
\[ \Sigma(p, F, n) = \Sigma(q_0, F, n) \text{ and } q_0 \text{ is } (F, n)\text{-determined (by } (F, n)\text{-determinedness of } p) \].

Having satisfied (1) and (2) at stage \( i \), note that there is a term \( \dot{s}_{i+1} \) such that

\[ q_i \models \text{“} \dot{s}_{i+1} \supseteq \dot{s}_i \text{ and } \dot{s}_{i+1} \text{ is an initial segment of } \dot{a} \text{”}. \]

Find \( q_{i+1, m_{i+1}, t_{i+1,j}} \) \((j < N)\) so that \( (q_{i+1, m_{i+1}}) <_F (q_i, n) \) and for each \( j \), \( q_{i+1} | \sigma_j \models \dot{s}_{i+1} = t_{i+1,j} \). Note that \( \Sigma(q_{i+1}, F, n) = \Sigma(q_i, F, n) = \Sigma(p, F, n) \) and \( q_{i+1} \) is \((F, n)\)-determined.

Having completed the induction, we let \( X \) be the set of unions of the columns of \([t_{ij}]\), i.e.,

\[ X = \left\{ x : \exists_j \left( x = \bigcup_{i \in \omega} t_{ij} \right) \right\} = \{ x_0, x_1, \ldots, x_{N-1} \}. \]

\( X \in [2^\omega]^{<\omega} \) because, as one shows by induction, the \( t_{i,j} \) are strictly increasing for fixed \( j \).

Now we modify the \( q_i \) slightly to satisfy condition (c): To get \( q^k \), let \( n_k \) be so large that

\[ \forall j < N(\text{dom } t_{n_k,j}) \supseteq k \text{ and } \forall k' < k(n_k > n_{k'}) \]

and let \( q^k = q_{n_k} \). Then for all \( j < N \),

\[ q^k | \sigma_j = q_{n_k} | \sigma_j \models \dot{a} \upharpoonright k = t_{ij} \upharpoonright k \]

and so

\[ q^k | \sigma_j \models \exists x \in X(x \upharpoonright k = \dot{a} \upharpoonright k). \]

Now by Proposition 2.9, condition (c) is satisfied and we are done. \( \square \)

From now on we will be a little more specific about the particulars of the iteration \( P_\alpha \). We shall assume that \( V \models “2^\omega = \omega_1 \text{ and } 2^{<\omega} = \omega_2” \). Let \( P \) be some strongly proper order defined in \( V \) by \( \theta(x) \) and witnessed by a constructible sequence of finite sets \( T = \{ T_n : n \in \omega \} \). Let \( P^\alpha \) denote the Sacks order. Let \( Z = \{ \alpha < \omega_2 : \text{cf } \alpha = \omega \} \).

Let \( P_{\omega_2} \) denote an \( \omega_2\)-stage countable support iteration such that for all \( \beta \in Z \), \( T^\beta = T \), and \( \{ \dot{A}^\beta_{\tau,n} : n \in \omega \upharpoonright \beta \tau \in \dot{Q}_\beta \}, \{ \dot{\varphi}^\beta_{\tau,n} : n \in \omega \upharpoonright \beta \tau \in \dot{Q}_\beta \} \) are terms so that \( \| \beta \|_{\dot{Q}_\beta} \leq c \) and \( \theta(\dot{Q}_\beta) \) and \( T^\beta \), \( \{ \dot{A}^\beta_{\tau,n} \}_\tau, \{ \dot{\varphi}^\beta_{\tau,n} \}_\tau \) witness that \( \dot{Q}_\beta \) is strongly proper. For \( \beta \in Z' = \omega_2 \setminus Z \), assume \( \| \beta \|_{\dot{Q}_\beta} \) is the Sacks order, and we will have corresponding \( T^\beta, \dot{A}^\beta_{\tau,n}, \dot{\varphi}^\beta_{\tau,n} \) for these coordinates as well. Using familiar techniques (which can be found in [Ba] and [J2]), we have the following theorem.

2.16 Theorem (i) If \( \beta \in Z' \) and \( \dot{P}_{\omega_2} \) is a term for the iteration \( P_{\omega_2} \) defined in \( V^{P_\beta} \), then \( \| \beta \|_{\dot{P}_{\beta,\omega_2}} \models \dot{P}_{\omega_2} \);

(ii) \( \forall \beta < \omega_2 \| \beta \|_{\dot{P}_{\beta,\omega_2}} \text{ CH}; \)

(iii) \( P_{\omega_2} \) has the \( \aleph_2\)-cc and all cardinals and cofinalities are preserved;

(iv) \( \| \omega_2 \|_\omega c = \omega_2 \).

Proof (Outline). (i) See [Ba, §5; J2, 7.13]; for each \( \beta \), the \( \beta \)th stage forces \( \dot{P}_{\beta,\omega_2} \) to be an iteration of some kind in \( V^{P_\beta} \); then since (a) for \( \beta \in Z' \) the factors “line up”,
and (b) the type of iteration being considered (i.e. countable support) is absolute for \( V, V[G_\beta] \) (by 2.12(iii)), the iteration in \( V^{\beta_0} \) is isomorphic to \( P_{\beta,\omega_2} \).

(ii) One shows by induction on \( \beta < \omega_2 \) that (a) \( \Vdash_\beta \text{CH} \) and (b) there is a dense set \( D_\beta \subset P_\beta \) of power \( \aleph_1 \). To construct the dense set, each factor must be forced to have power \( \leq \aleph_1 \) and CH is used; since \( |D_\beta| \leq \aleph_1 \), an unpublished observation of Baumgartner (which says that whenever CH holds, posets of power \( \leq \aleph_1 \) which do not collapse \( \aleph_1 \) preserve CH) guarantees that \( \Vdash_\beta \text{CH} \).

(iii) A \( \Delta \)-system argument gives the \( \aleph_2 \)-cc. The rest follows from 2.13.

(iv) We have added \( \aleph_2 \) Sacks reals; because of CH and the fact that \( 2^{\omega_1} = \omega_2 \), the continuum is at most \( \omega_2 \). \( \square \)

2.17 Remark In our applications, a mixed iteration \( P_{\omega_2} \) of just two orders of cardinality \( c \), as described above, will suffice. As we shall see, the only restrictions to increasing the number of factors are (a) the set \( Y \) of coordinates \( \beta < \omega_2 \) for which \( \Vdash_\beta \) “\( Q_\beta \) is the Sacks order” should include the set \( \{0\} \cup \{\gamma: \text{cf} \gamma = \omega_1\} \), and (b) for all \( \beta \in Y \), \( \Vdash_\beta P_{\beta,\omega_2} \equiv \tilde{P}_{\beta,\omega_2} \). Thus, for example, if we let \( Y = \{0\} \cup \{\gamma: \text{cf} \gamma = \omega_1\} \cup \{\mu, \nu: \text{cf} \mu = \omega_1 \text{ and } \text{cf} \nu = \omega_1\} \), then since for every pair \( \mu < \nu \) of successive members of \( Y \), the interval \( (\mu, \nu) \) is a copy of \( (0, \omega_1) \), we can obtain an iteration of \( \omega_1 \) many strongly proper orders—so that (a) and (b) are satisfied—by (essentially) repeating the sequence of orders defined over \( (0, \omega_1) \) over each interval \( (\mu, \nu) \), and putting the Sacks order elsewhere.

In the remainder of this section, we show how iterations of two factors described above yield forcing extensions which model Miller’s result, i.e., that for every \( X \subset 2^\omega \) of power \( c \), there is a continuous \( f: 2^\omega \to 2^\omega \) such that \( f''X = 2^\omega \). The main idea is that each new real can be mapped continuously onto the first Sacks real by a map coded in \( V \). Then, given \( X \in V[G_{\omega_2}] \), \( X \subset 2^\omega \), which cannot be mapped continuously onto \( 2^\omega \), one shows that \( X \subset V[G_\alpha] \) for some \( \alpha < \omega_2 \) by using the map above to force each new real not in \( V[G_\alpha] \) to lie outside of \( X \). The proofs follow [M2] closely. As a notational convenience, we will henceforth identify \( s \in 2^{<\omega} \) with the map \( \hat{s}: \{0\} \to 2^{<\omega} \) defined by \( \hat{s}(0) = s \).

2.18 Lemma If \( p \Vdash \" \hat{a} \not\in V \text{ and } \hat{a} \in 2^{\omega_n}, n \in \omega, F \in [\omega_2]^{<\omega}, \text{ and } p \) is \( (F, n) \)-determined, then there are \( q \in P_{\omega_2} \) and a collection \( \{C_s: s \in q(0) \cap 2^n\} \) of disjoint clopen subsets of \( 2^\omega \) such that

(i) \( (q, n) \leq_F (p, n) \), and

(ii) \( \forall s \in q(0) \cap 2^n \exists s | s \Vdash \hat{a} \in C_s \).

Proof. Let \( \{s_0, \ldots, s_{N-1}\} \) enumerate \( p(0) \cap 2^n \). Apply Lemma 2.15 using \( p|s_0 \) and \( Y = \emptyset \) to obtain a finite set \( X_0 \subset 2^\omega \cap V \) and conditions \( q_0^k \leq p|s_0 \), \( k \in \omega \), such that

\[
q_0^k \Vdash \exists x \in X_0(\hat{a} \vdash k = x \upharpoonright k).
\]

Having defined \( X_i \), \( q_i^k \) for \( i < N - 1 \), apply Lemma 2.15 again, using \( p|s_{i+1} \) and \( Y = \bigcup_{j \leq i} X_j \), to obtain \( q_{i+1}^k \leq p|s_{i+1} \) and a finite set \( X_{i+1} \subset 2^\omega \cap V \) disjoint from \( Y \) such that

\[
q_{i+1}^k \Vdash \exists x \in X_{i+1}(\hat{a} \upharpoonright k = x \upharpoonright k).
\]

Let \( k \) be large enough so that if \( i \neq j, x_i \in X_i, x_j \in X_j \) then \( x_i \upharpoonright k \neq x_j \upharpoonright k \). Let \( C_{s_i} = \bigcup_{x \in X_i} U_{x \upharpoonright k} \) (where \( U_t = \{f \in 2^\omega: f \supseteq t\} \)). Now glue together the \( q_i^k \).
as follows: Let \( q(0) = \bigcup_{n < \omega} q^n(0) \). Notice \((q(0), n) \leq (p(0), n)\). For \( 0 < \beta < \omega_2 \), proceed by induction to define \( q \upharpoonright \beta \) using as the induction hypothesis the following:

(a) \((q \upharpoonright \beta, n) \leq F \cap \beta \) \((p \upharpoonright \beta, n)\), and
(b) \( q(s_i) \upharpoonright \beta = q^i \upharpoonright \beta \).

For limit \( \beta \), let \( q \upharpoonright \beta \) be the union of the \( q \upharpoonright \beta' \), \( \beta' < \beta \). If \( q \upharpoonright \beta \) is defined, let \( q(\beta) \) be a term defined by cases:

\[
(\forall i < N)(q(s_i) \upharpoonright \beta \vdash q(\beta) = q^i(\beta)).
\]

By (b) of the induction hypothesis, \( q(s_i) \upharpoonright \beta \vdash "(q(\beta), n) \leq (p(\beta), n)" \) if \( \beta \in F \), and so (a) is satisfied. (Note that \( q \upharpoonright \beta \) is \((\{0\}, n)\)-determined.)

It is clear that the resulting \( q \) satisfies the conclusion of the lemma. □

The fact that any new real appearing at any stage can be mapped continuously onto the first Sacks real by a \( V \)-coded map derives from this lemma, and in particular, from the fact that having the Sacks order on the first coordinate allows us to paste together conditions below \( p \) of our choosing to obtain a condition which is “fat” with respect to \( p \) (and hence preparing for fusion). This property appears to be unique to the Sacks order (at least among strongly proper orders which add reals).

2.19 **Theorem** If \( p \vdash \dot{a} \notin V \) and \( \dot{a} \in 2^\omega \), there is \( q \leq p \) and for each \( n \in \omega \) there is \( m \geq n \) and a family \( \{C_s : s \in q(0) \cap 2^m\} \) of disjoint clopen subsets of \( 2^\omega \) such that

\[
\forall s \in p(0) \cap 2^m(q|s \vdash \dot{a} \in C_s).
\]

**Proof.** Build a fusion sequence \( \{(q_n, F_n, m_n) : n \in \omega\} \) and disjoint clopen sets \( \{C_s : s \in q_n(0) \cap 2^{m_n}\} \) for \( n > 0 \) so that

(a) \( q_{n+1} \) is \((F, n)\)-determined;
(b) \( (q_{n+1}, m_{n+1}) <_{F_n} (q_n, m_n) \);
(c) \( \forall s \in q_n(0) \cap 2^{m_n}(q_{n+1}|s \vdash \dot{a} \in C_s) \).

WLOG, assume \( 0 \in \text{suppt}(p) \) and begin building the sequence by letting \( 0 \in F_0, q_0 = p \), and letting \( m_0 \) be arbitrary. Now if \( (q_n, F_n, m_n) \), \( n > 0 \), has been defined, use 2.12(i) to get \( q' \) so that

\[
(\ast) \quad (q', m_n) <_{F_n} (q_n, m_n) \quad \text{and} \quad q' \text{ is } (F, n)\text{-determined}.
\]

Let \( q'', \{C_s : s \in q_n \cap 2^{m_n}\} \) be as in Lemma 2.17 and finally let \((q_{n+1}, m_{n+1}) <_{F_n} (q'', m_n) \) be as in 2.12(i) again. Choose \( F_{n+1} \supseteq F_n \) using an appropriate recipe to ensure \( \bigcup_n F_n = \bigcup_n \text{suppt } q_n \). Now any fusion of \( \{(q_n, F_n, m_n) : n \in \omega\} \) is the desired condition. □

2.20 **Corollary** If \( p \vdash \dot{a} \notin V \) and \( \dot{a} \in 2^\omega \), there is \( q \leq p \) and for each \( n \in \omega \) a family \( C_n = \{C_s : s \in q(0) \cap 2^m\} \) of disjoint clopen subsets of \( 2^\omega \) such that

(a) \( C_n \) is a partition of \( 2^\omega \);
(b) if \( s \subseteq t \) then \( C_t \subseteq C_s \);
(c) \( q|s \vdash \dot{a} \in C_s \).
Remark that \( \hat{\omega} \) (for iterated Sacks forcing) that for each

\[
q \models_{\omega_2} \text{“} f: 2^\omega \to [q(0)], \ \dot{f} \text{ is continuous, and } \dot{f}(\dot{a}) = x_0 \text{”},
\]

where \( x_0 \) denotes the first Sacks real.

2.22 Remark \( g \) has a code in \( V \) if the sequence \( \langle (g^{-1}(U_s); s \in 2^{<\omega}) \rangle \) is coded in \( V \). Note this sequence is coded as a subset of \( \omega \). As above, we denote the evaluation in \( V \) of such a code with an undotted letter (say \( f \)) and its evaluation in an extension by a dotted letter (say \( \dot{f} \)).

Proof of 2.21. Let \( q \leq p \) and \( \{C_n; n \in \omega \} \) be as in the corollary. Define \( f: 2^\omega \to [q(0)] \) in \( V \) by putting

\[
s \subset f(x) \iff x \in C_n.
\]

Now, referring to 2.19, \( f \) is a function because of (a) and (b); \( f \) is continuous by clopenness of the \( C_n \); and \( q \models \dot{f}(\dot{a}) = x_0 \) because of (c).

2.23 Theorem \( \models_{\omega_2} \text{“} Every set of reals of power } c \text{ is mapped uniformly continuously onto } [0, 1] \text{”}.

Proof. By our remarks in the Introduction, it suffices to reproduce Miller’s proof (for iterated Sacks forcing) that for each \( X \subset 2^\omega \), \( |X| = c \), there is a continuous \( f: 2^\omega \to 2^\omega \) for which \( f''X = 2^\omega \). Assume there is an \( X \) for which the statement fails; for each \( f: 2^\omega \to 2^\omega \), let \( z_f \in 2^\omega \setminus f''X \). Let \( C^\beta(2^\omega) = \{f \in 2^\omega \setminus V[G_{\omega_2}]; f \text{ coded in } V[G\beta]\} \), where \( G_{\omega_2} \) is \( P_{\omega_2} \)-generic over \( V \).

Claim. There is \( \beta \in Z' \) such that for all \( f \in C^\beta(2^\omega) \), \( z_f \in V[G\beta] \cap 2^\omega \).

Proof of Claim. Use the \( \aleph_2 \)-cc to construct a Löwenheim-Skolem type argument as in [BL, §4.5], which yields a club of \( \beta \) with the property that for all \( \gamma < \beta \) if \( f \in C^\gamma(2^\omega) \) then \( z_f \in V[G_{\gamma'}] \) for some \( \gamma' < \beta \). Thus there is such a \( \beta \) of cofinality \( \omega_1 \) (hence \( \beta \in Z' \)); now if \( f \in C^\beta(2^\omega) \) with code \( c \in 2^\omega \), use 2.14 to obtain \( \gamma < \beta \) such that \( c \in V[G_{\gamma}] \). Then by the choice of \( \beta \), \( z_f \in V[G\beta] \).

Now by 2.16(l) we may assume that for each \( f \in C^\beta(2^\omega) \), \( z_f \in 2^\omega \cap V \). We show \( \models_{\omega_2} X \subset V \) by showing that if \( p \models \text{“} \dot{a} \in 2^\omega \text{ and } \dot{a} \notin V \text{”} \) then there is \( \dot{q} \leq p \) for which \( \dot{q} \models \dot{a} \notin X \).

Let \( q \leq p \) and \( f: 2^\omega \to [q(0)] \) be as in 2.20. Define \( g = g_1 \circ g_2: [q(0)] \to 2^\omega \) as follows: \( g_2: [q(0)] \to 2^\omega \times 2^\omega \) is a homeomorphism and \( g_1: 2^\omega \times 2^\omega \to 2^\omega \) is projection onto the first coordinate. Note that for each \( z \in 2^\omega \), \( g^{-1}(z) = [r_z] \) is a perfect subset of \( [q(0)] \). Define \( g_2(z) = r_z \) and for \( \beta > 0 \), \( g_2(\beta) = q(\beta) \); then \( q \models \dot{g}(x_0) = z \). Thus let \( \dot{q} \models \dot{g}(\dot{f}(\dot{a})) = z \) and \( \dot{q} \models z \notin \dot{g}(\dot{f}(X)). \) It follows that \( \dot{q} \models \dot{a} \notin X \).
3. Proofs and questions

In this section we complete the proofs of the results introduced in §0 and state several open problems along the way. Henceforth, let us denote by $V'$ the model obtained by forcing with a mixed iteration as in §2 using the IOER order on the $Z$-coordinates. We observe that $V'$ satisfies the Generalized Borel Conjecture by Theorem 2.23, the fact that forcing with the IOER order makes the ground model reals have strong measure zero, and that the mixed iteration is $\omega$-bounding. (This proves Theorem 0.0.) By the same fact,

$$V' \models \text{non}(U_0) = \mathfrak{c}.$$  

As was observed in §0 (see remark following 0.9) $\text{non}(U_0) = \text{non}(L)$; so by Grzegorek's result (0.7(a)), we have in $V'$ a $U_0$ set (hence $2^\mathfrak{c}$ $U_0$ sets) of power $\mathfrak{c}$. This proves Theorem 0.3.

As noted before, Theorem 0.0 is a somewhat unusual result for hereditary classes over $\mathbb{R}$. For a class $A \subseteq (s)_0$, we write GBC($A$) if it is consistent that $A = [\mathbb{R}]^{<\mathfrak{c}}$. We observed in the introduction that $\neg$GBC($U_0$) and $\neg$GBC(AFC); similarly, $\neg$GBC($\gamma$) ($\gamma$ sets are defined in [GM]).

On the other hand, GBC does hold for a few classes. Letting $C' = \{X \subseteq \mathbb{R}: f''X \in C \text{ for all continuous } f\}$ ($C'$ was introduced by Rothberger in [R]), it is clear that GBC($C$) $\rightarrow$ GBC($C'$). It is well known that under MA,

$$\{X: X \text{ is a } Q \text{ set} \} = [\mathbb{R}]^{<\mathfrak{c}}.$$

(A $Q$ set is a set all of whose subsets are relative $G_\delta$'s; see [M3].) Finally, an unpublished result of Miller states that GBC($\lambda'$) holds in Laver's model [La]. We are left with the following questions:

3.0 Question. Does GBC hold for con or P?

Recall that $(\ast)$ is the statement that every set of reals of power $\mathfrak{c}$ satisfies $M$. As was mentioned in the introduction, a model of “$(\ast)+$ there is an AFC set of power $\mathfrak{c}$” could be obtained if there were a strongly proper order forcing the ground model reals to be meager. Although all our examples of strongly proper orders force the ground reals to be “badly” nonmeager (what is actually forced is the statement “Every meager set is contained in a meager set coded in the ground model”), the
axioms in 1.0 do not seem to imply this. The reason appears to be that the Sacks, IOER, and Silver orders all satisfy the following additional axiom which does not follow readily from the other axioms:

(5) For each \( s \in A_{p,n} \) and each \( q \leq p \mid s \) there is \((r,n) \leq (p,n)\) so that \( r_n = p \).

Adding (5) to the list in 1.0, we can show that iterations satisfy a similar property and hence that each meager set in \( V[G_{\omega_2}] \) is covered by a meager set coded in \( V \) (see [M1, §7.2] for a prototypical proof). A natural question is:

3.1 Question. Does Axiom (5) follow from Axioms 1–4?

Models obtained by forcing as in §2 must satisfy “\( \text{cov}(\mathcal{L}) < c \) and \( \text{cov}(\mathcal{K}) < c^+ \)” since (⋆) itself implies these relations (for example, if \( \text{cov}(\mathcal{K}) = c \) there is a \( c \)-Luzin set). However, though our models must satisfy “\( d < c \)” (since the iterations are \( \omega^\omega \)-bounding), it is unclear whether (⋆) implies this. More generally, we ask:

3.2 Question. Is “\( \text{cov}(\mathcal{L}) < c \) and \( \text{cov}(\mathcal{K}) < c^+ \)” consistent?

Note that a positive answer would give a model of “(⋆) + there are \( 2^c \lambda \) sets of power \( c \).

We now turn to a discussion of the class \( J = \{ X \subset \mathbb{R} : \neg\text{M}(X) \} \) introduced earlier. We first note that unlike \( C \), \( J \) must contain uncountable members, for if CH holds, there is a Luzin set; if CH fails, there is a set \( X \subset \mathbb{R} \) with \( \omega < |X| < c \) (and such a set is in \( J \)). We have

3.3 Proposition \( J \) has uncountable members. □

We now show that \( J \) is a \( \sigma \)-ideal; we use an argument of Miller’s which he used to show that \( I \) (mentioned in the Introduction) is closed under countable unions.

3.4 Proposition \( J \) is a \( \sigma \)-ideal.

Proof. \( J \) is hereditary since uniformly continuous maps extend to the whole space. To see \( J \) is closed under countable unions, first note that \( J \) is closed under uniformly continuous maps and recall that \( J \) is a subclass of the \( \sigma \)-ideal \( (s)_0 \). Thus, if \( X_n \in J \) and \( X = \bigcup_n X_n \) for each \( n \in \omega \), and \( f: X \rightarrow [0,1] \) is uniformly continuous, then

\[
\left( f'' x \right)_{n} = \bigcup_n f'' X_n \in (s)_0;
\]

thus \( f'' X \neq [0,1] \). Now since \( f \) was arbitrary, it follows that \( X \in J \). □

Next, we restate and prove Theorem 0.5:

Theorem (a) ZFC ⊢ \( U_0 \neq J \) and AFC ⊄ \( J \);
(b) ZFC + CH ⊢ \( U_0 \cap AFC \subset J \) and \( J \subset U_0 \cup AFC \);
(c) \( \text{Con}(\text{ZFC}) \rightarrow \text{Con}(\text{ZFC}) + U_0 \ \text{\unlhd} \ J + AFC \ \text{\unlhd} \ J \);
(d) \( \text{Con}(\text{ZFC}) \rightarrow \text{Con}(\text{ZFC} + J \ \text{unlhd} \ U_0) \).

Proof. (a) We use 0.7. If \( \text{non}(\mathcal{L}) < c \), there is \( X \in [\mathbb{R}]^{<c} \setminus U_0 \) and clearly such \( X \) is in \( J \). If \( \text{non}(\mathcal{L}) = c \), argue as in the proof that in ZFC there is always a member of \( (s)_0 \) satisfying \( M \): Note that \( U_0 \) is closed under 1-1 continuous preimages (see [M3, 9.3.1]) and so if \( f \) is a bijection from a \( U_0 \) set in \( 2^\omega \) onto \( 2^\omega \), then \( f \subset 2^\omega \times 2^\omega \) is \( U_0 \). Now projection onto the second coordinate gives rise to a uniformly continuous map from a \( U_0 \) set onto \( [0,1] \).
For AFC, if non(Å) < c we have an X ∈ [R]<c\Å as before. If non(Å) = c, argue as above using Å (which is closed under 1-1 continuous pre-images; see [G2]) in place of Å0. We get a uniformly continuous map from an Å (hence AFC) set onto [0, 1].

(b) To see Å0 ∩ AFC ≠ J, we take any uncountable set X ∈ Å0 ∩ Å (a Hausdorff gap for example; see [La, M3]). By CH, |X| = c. Now argue as in part (a) to get a uniformly continuous map from X onto [0, 1]. To see that J ⊂ Å0∪Å, consider the union of a Luzin set and a Sierpinski set.

(c) The required model is obtained by iterated perfect set forcing [M2]; it has already been observed that Å0 ∪ Å ⊂ [R]<c in this model.

(d) The model is that of Theorem 0.0 in which J = [R]<c and non(Å) = c. □

Next we prove Lemma 0.9; we begin with the following lemma.

3.5 Lemma The following are equivalent for any perfect Polish space Z and X ⊂ Z:

(i) X ∈ Å.

(ii) X is meager and for all nowhere dense perfect sets P, X∩P is meager relative to P.

(iii) For all P ⊂ Z, if P is perfect nowhere dense or if P is the closure of a basic open set, then X∩P is meager relative to P.

Proof. (i) → (ii) and (ii) → (iii) are immediate. For (iii) → (i) let Q′ = P\int P and write Q′ = Q ∪ C, where Q is perfect nowhere dense and C is countable. Note that for each basic open set B ⊂ Z, X∩B is meager relative to B. Thus X∩P is meager relative to int P, hence to P; also, X∩Q, hence X∩Q′, is meager relative to P. The result follows. □

We now restate and prove Lemma 0.9:

Lemma (a) non(Å) = non(Å0); and (b) non(Å) = non(Å) = non(Å).

Proof. (a) was proven in the remarks following 0.9. For (b), first note that non(Å) ≤ non(Å) ≤ non(Å). We prove non(Å) ≤ non(Å): Suppose Y ∉ Å. Let f: X → Y be 1-1 continuous so that X ∉ Å. By 3.5(iii), there is a perfect nowhere dense set P such that X∩P is nonmeager relative to P. Let h: P → 2ω be a homeomorphism and g: 2ω → [0, 1] the canonical onto map. Then g(h(X∩P)) ∉ Å and |g(h(X∩P))| ≤ |Y|. □

Finally we prove Theorem 0.6:

Theorem (a) In the random real model (or if c is real-valued measurable) we have Å0 ⊆ Å.

(b) In the Cohen model, Å ⊆ Å0 (in fact, Å ⊆ Å′).

(c) Con(ZFC) → (Con(ZFC) + either ϕ or ψ) where ϕ = “Å ⊆ Å0” and ψ = “every set of reals of power c satisfies M and there are 2c many AFC sets of power c”.

Proof. (a) In [M2], Miller shows that in the model obtained by adding ω2 random reals to a model of GCH, every Å0 set has power < c. Now, using Lemma 0.9(b) and the fact the model also satisfies “non(Å) = c”, we get that “Å0 ⊆ Å” holds as well. Using 0.7(b), we conclude that inclusion is proper.

To obtain the result from the theory “ZFC + c is real-valued measurable”, begin with an atomless, nonzero, c-additive probability measure µ defined on P(Å). By
[Ma, 3.1(i)], $X \in U_0$ iff each diffused measure on $\mathcal{B}(X)$ (i.e. the Borel sets relative to $X$) vanishes identically. (Say $\mu$ is diffused if it takes singletons to zero.) Thus, since $\mu$ is diffused (being atomless) and its properties are preserved under bijections, there is no $U_0$ set of cardinality $c$. Thus, as above, it suffices to prove $\text{non}(\mathcal{K}) = c$. Referring to Diagram 2, it is enough to prove $\text{cov}(\mathcal{L}) = c$. Suppose $\{N_\alpha : \alpha < \kappa\}$ is a cover of $[0,1]$ by Lebesgue measure zero sets where $\kappa \leq c$; we may assume each $N_\alpha$ is a Borel set. If $\mathcal{B} = \{\text{Borel sets on } [0,1]\}$, then $\mu \upharpoonright \mathcal{B}$ is a finite diffused Borel measure and there is a continuous function $F : [0,1] \to [0,1]$ such that $\lambda \upharpoonright \mathcal{B} = (\mu \circ F^{-1}) \upharpoonright \mathcal{B}$ (where $\lambda$ is Lebesgue measure). Hence $\{F^{-1}(N_\alpha) : \alpha < \kappa\}$ is a cover of $[0,1]$ by $\mu$-measure zero sets; by $c$-additivity of $M$, $\kappa = c$, and the result follows.

(b) In [M2], Miller shows that in the model obtained by adding $\omega_2$ Cohen reals to a model of GCH, every set of reals of power $c$ contains a 1-1 continuous image of a Luzin set. Since such sets are not AFC and since the latter is closed under 1-1 continuous preimages, it follows that no AFC set has cardinality $c$. Since the Cohen model satisfies “$\text{cov}(\mathcal{K}) = c$” (see [K]), and since $\text{cov}(\mathcal{K}) \leq \text{non}(C'')$ (Theorem 0.8 above), it follows that $\text{AFC} \subset C''$. The inclusion is proper since there is a Luzin set of power $c$.

(c) Consider the model $V'$ of Theorem 0.0. If there is an AFC set of power $c$ in this model, then there are $2^c$ of them, and $\psi$ holds. If every AFC set has cardinality $< c$, then since $\text{non}(\mathcal{L}) = c$, we can use 0.7(a) and 0.9(a) again to conclude that $\text{AFC} \subset U_0$. 
REFERENCES


