DENSITY, FORCING, AND THE COVERING PROBLEM

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Abstract. We present a notion of forcing that can be used, in conjunction with other results, to show that there is a Martin-Löf random set $X$ such that $X \not\geq_T \emptyset'$ and $X$ computes every $K$-trivial set.

1. Introduction

Hirschfeldt, Nies and Stephan [6] proved that if $A \in 2^\omega$ is c.e. and there is a Martin-Löf random $X \geq_T A$ that does not computes $\emptyset'$, then $A$ is $K$-trivial. Stephan asked if this gives a characterization of the c.e. $K$-trivial sets. Each $K$-trivial is computable from a c.e. $K$-trivial, so this amounts to asking:

If $A$ is $K$-trivial, is there a Martin-Löf random $X \not\geq_T \emptyset'$ that computes $A$?

The history and significance of this question, known as the covering problem, is presented in a summary paper by the authors of this paper and Bienvenu, Greenberg, Kučera, Nies and Turetsky [1]. The present paper, combined with theorems of Bienvenu, Greenberg, Kučera, Nies and Turetsky [2], and Bienvenu, Hölzl, Miller and Nies [4], gives a strong affirmative answer to the covering problem:

(a) There is a Martin-Löf random $X \not\geq_T \emptyset'$ that computes every $K$-trivial.

Furthermore, we get two interesting refinements:

(b) There is a Martin-Löf random $X <_T \emptyset'$ that computes every $K$-trivial.

(c) If $\langle A_n : n \in \omega \rangle$ is a countable sequence of non-$K$-trivial sets, then there is a Martin-Löf random $X \not\geq_T \emptyset'$ that computes every $K$-trivial but no $A_n$.

By (c), for example, there is an incomplete Martin-Löf random set $X$ such that the $\Delta^0_2$ sets computed by $X$ are precisely the $K$-trivial sets. This $X$ and Chaitin’s $\Omega$ are Martin-Löf random sets that form an exact pair for the ideal of $K$-trivial sets (i.e., $A \leq_T X, \Omega$ if and only if $A$ is a $K$-trivial set).

Our contribution to the solution of the covering problem comes out of a careful analysis of Lebesgue density for $\Pi^0_1$ classes. Let $\mu$ be the uniform measure on Cantor space. If $\tau \in 2^{<\omega}$ and $P$ is a measurable set in Cantor space, then we define

$$\mu_\tau(P) = \frac{\mu(P \cap [\tau])}{\mu([\tau])}.$$
Given any measurable set $P$ and $X \in 2^\omega$, we define $\rho(P \mid X) = \lim\inf_i \mu_{X \restriction i}(P)$.

We call $X \in 2^\omega$ a density-one point if for every $\Pi_0^1$ class $P$ it is the case that

$$X \in P \implies \rho(P \mid X) = 1.$$ 

If for every $\Pi_0^1$ class $P$ we have $X \in P \implies \rho(P \mid X) > 1$, then $X$ is called a positive density point. In Section 2, we present a notion of forcing that separates density-one from positive density on the Martin-Löf random sets. In other words, if $X$ is a sufficiently generic set for this notion of forcing then:

1. $X$ is Martin-Löf random,
2. $X$ is not a density-one point,
3. $X$ is a positive density point.

Properties (1), (2) and (3) of generic sets will be established by Claims 2.1, 2.2 and 2.3, respectively. This forcing notion, in conjunction with the following two theorems, provides a solution to the covering problem.

**Theorem 1.1** (Bienvenu, Hölzl, Miller and Nies [3, 4]). If $X \geq_T \emptyset'$ and Martin-Löf random, then there exists a $\Pi_0^1$ class $P$ such that $X \in P$ and $\rho(P \mid X) = 0$.

We should note that Bienvenu, et al. prove Theorem 1.1 for density on the unit interval. However, the Cantor space version follows immediately from the proof given in [4, Theorem 20].

**Theorem 1.2** (Bienvenu, Greenberg, Kučera, Nies and Turetsky [2]). If $X \in 2^\omega$ is Martin-Löf random and not a density-one point, then $X$ computes every $K$-trivial set.

The original proof of Theorem 1.2, given in [2], involves several steps. A direct proof, though one relying on more of the theory of $K$-triviality, is given by Bienvenu, Hölzl, Miller and Nies [3].

By Theorem 1.1 properties (1) and (3) imply that $X$ does not compute $\emptyset'$. By Theorem 1.2 properties (1) and (2) imply that $X$ computes all $K$-trivial sets. This shows (a). In Claim 2.4, we show that if $A$ is not $K$-trivial and $X$ is sufficiently generic for our notion of forcing, then $X \not\leq_T A$. This gives us (c); in a sense, our forcing notion is perfectly tuned to constructing incomplete Martin-Löf random sets that compute all $K$-trivial sets. To show (b), we effectivize the forcing notion in Section 3 to show that there is a $\Delta_2^0$ set $X$ with properties (1), (2) and (3).

2. The forcing notion

Fix a nonempty $\Pi_0^1$ class $P \subseteq 2^\omega$ that contains only Martin-Löf random sets. Our forcing partial order $\mathbb{P}$ consists of conditions of the form $\langle \sigma, Q \rangle$, where

- $\sigma \in 2^{<\omega}$,
- $Q \subseteq P$ is a $\Pi_0^1$ class,
- $[\sigma] \cap Q \neq \emptyset$,
- There is a $\delta < 1/2$ such that $(\forall \rho \supseteq \sigma) [\rho] \cap Q \neq \emptyset \implies \mu_{\rho}(Q) + \delta \geq \mu_{\rho}(P)$.

We say that $\langle \tau, R \rangle$ extends $\langle \sigma, Q \rangle$ if $\tau \supseteq \sigma$ and $R \subseteq Q$. Let $\lambda$ be the empty string.

Note that $\langle \lambda, P \rangle \in \mathbb{P}$, with $\delta = 0$, so $\mathbb{P}$ is nonempty.

If $G \subseteq \mathbb{P}$ is a filter, let $X_G = \bigcup_{\langle \sigma, Q \rangle \in G} \sigma$. In general, $X_G \in 2^{\leq\omega}$. The following claim is trivial to verify and it establishes that if $G$ is sufficiently generic, then $X_G$ is infinite and, in fact, a Martin-Löf random set.

**Claim 2.1**.
(1) If \( (\sigma, Q) \in \mathbb{P} \) and \( \tau \succ \sigma \) is such that \( [\tau] \cap Q \neq \emptyset \), then \( \langle \tau, Q \rangle \in \mathbb{P} \).

(2) If \( G \subseteq \mathbb{P} \) is sufficiently generic, then \( X_G \in P \) (hence it is a Martin-Löf random set).

Claim 2.2. If \( G \subseteq \mathbb{P} \) is sufficiently generic, then \( \rho(P \mid X_G) \leq 1/2 \), so \( X_G \) is not a density-one point.

Proof. Fix \( n \). We will show that the conditions forcing

\[
(2.1) \quad (\exists l \geq n) \, \mu_{X_G \upharpoonright l}(P) < 1/2
\]

dense in \( \mathbb{P} \). Let \( (\sigma, Q) \) be any condition and let \( \delta \) witness that \( (\sigma, Q) \in \mathbb{P} \). Take \( m \) such that \( 2^{-m} < 1/2 - \delta \). Let \( Z \) be the left-most path of \( [\sigma] \cap Q \). The set \( Z \) is Martin-Löf random and consequently contains arbitrarily long intervals of 1's. Take \( \tau \succ \sigma \) such that \( \tau \upharpoonright m \prec Z \) and \( |\tau| \geq n \). Because \( Z \) is the left-most path in \( Q \) it follows that \( \mu_\tau(Q) \leq 2^{-m} \) and so

\[
\mu_\tau(P) \leq \mu_\tau(Q) + \delta < 2^{-m} + \delta < 1/2.
\]

Hence the condition \( \langle \tau, Q \rangle \) extends \( (\sigma, Q) \) and forces \( (2.1) \). \( \square \)

Claim 2.3. Let \( S \subseteq 2^\omega \) be a \( \Pi^0_1 \) class and let \( (\sigma, Q) \in \mathbb{P} \). There is an \( \varepsilon > 0 \) and a condition \( (\tau, R) \) extending \( (\sigma, Q) \) such that either

- \( [\tau] \cap S = \emptyset \), or
- If \( X \in R \), then \( \rho(S \mid X) \geq \varepsilon \).

Therefore, if \( G \subseteq \mathbb{P} \) is sufficiently generic, then \( X_G \) is a positive density point.

Proof. If there is a \( \tau \succ \sigma \) such that \( [\tau] \cap S = \emptyset \) and \( [\tau] \cap Q \neq \emptyset \), then let \( \langle \tau, Q \rangle \) be our condition.

Otherwise, it follows that \( S \cap [\sigma] \supseteq Q \cap [\sigma] \). In this case let \( \delta \) witness that \( (\sigma, Q) \in \mathbb{P} \). Take \( \varepsilon \) to be a rational greater than 0 and less than \( \min\{1/2 - \delta, \mu_\sigma(Q)\} \).

(Note that \( \mu_\sigma(Q) > 0 \) because \( [\sigma] \cap Q \) is a non-empty \( \Pi^0_1 \) class containing only Martin-Löf random sets.) Consider the \( \Pi^0_1 \) class

\[
Q_\sigma^\varepsilon = \{ X \in Q \cap [\sigma] : (\forall n \geq |\sigma|) \, \mu_{X \upharpoonright n}(Q) \geq \varepsilon \}.
\]

We will show that \( (\sigma, Q_\sigma^\varepsilon) \) is the required condition.

Let \( M \) be the set of minimal strings in \( \{ \rho \supseteq \sigma : \mu_\rho(Q) < \varepsilon \} \). Then \( M \) is prefix-free and \( Q_\sigma^\varepsilon = Q \cap [\sigma] \setminus Q \cap [M] \). Summing over \( M \) gives us \( \mu_\sigma(Q \cap [M]) < \varepsilon \). Hence \( \mu_\sigma(Q_\sigma^\varepsilon) > \mu_\sigma(Q) - \varepsilon > 0 \). This proves that \( [\sigma] \subseteq Q_\sigma^\varepsilon \neq \emptyset \).

If \( \tau \succ \sigma \) and \( [\tau] \cap Q_\sigma^\varepsilon \neq \emptyset \), we can use the same argument to show that \( \mu_\tau(Q_\sigma^\varepsilon) > \mu_\tau(Q) - \varepsilon \). Because \( [\tau] \cap Q \neq \emptyset \),

\[
\mu_\tau(P) \leq \mu_\tau(Q) + \delta < \mu_\tau(Q_\sigma^\varepsilon) + \varepsilon + \delta.
\]

Hence \( \varepsilon + \delta < 1/2 \) witnesses that \( (\sigma, Q_\sigma^\varepsilon) \) is a condition.

Note that if \( X \in Q_\sigma^\varepsilon \), then \( \rho(Q \mid X) \geq \varepsilon \). This implies that \( \rho(S \mid X) \geq \varepsilon \) because \( S \cap [\sigma] \supseteq Q \cap [\sigma] \), proving the claim. \( \square \)

A difference test is a \( \Pi^0_1 \) class \( R \) and a uniform sequence of open sets \( \langle U_n : n \in \omega \rangle \) such that for all \( n \), \( \mu(U_n \cap R) \leq 2^{-n} \). A set \( X \) is captured by such a difference test if \( X \in \bigcap_{n \in \omega} U_n \cap R \). We call a set \( X \) difference random if it is not captured by any difference test. Difference randomness was introduced by Franklin and Ng [5]. They showed that \( X \) is difference random if and only if \( X \) is Martin-Löf random and \( X \not\subseteq_T \emptyset' \). Hence Claims 2.1 and 2.3 along with Theorem 1.3 establish that if \( G \subseteq \mathbb{P} \) is sufficiently generic, then \( X_G \) is difference random.
Claim 2.4. Assume that $A \in 2^\omega$ is not $K$-trivial, $\langle \sigma, Q \rangle \in \mathbb{P}$, and $\Phi$ is a Turing functional. There is a $\tau \in 2^{<\omega}$ such that $\langle \tau, Q \rangle$ extends $\langle \sigma, Q \rangle$ and

$$\forall X \in [\tau] \cap Q \ [\Phi^X = A \implies X \text{ is not difference random}].$$

Therefore, if $G \subseteq \mathbb{P}$ is sufficiently generic relative to $A$, then $X_G$ does not compute $A$.

Proof. If there is a $\rho \succ \sigma$ and an $n$ such that $\Phi^\rho(n) \uparrow \neq A(n)$ and $\rho \cap Q \neq \emptyset$, then take $\tau = \rho$.

Assume that no such $\rho$ and $n$ exist. Define $V_n = \{ X \in 2^\omega : X \in U_n[\Phi|^X] \}$, where $U_n[\mathbb{Z}]$ is the $n$th level of the universal Martin-Löf test relative to $Z$. If $X \in V_n \cap [\sigma] \cap Q$, then because $\Phi^X$ is not incompatible with $A$, we have $X \in U_n[\Phi|^X] \subseteq U_n[A]$. Hence $\mu(V_n \cap [\sigma] \cap Q) \leq \mu U_n(A) \leq 2^{-n}$. In other words, $Q$ and $\langle V_n \cap [\sigma] : n \in \omega \rangle$ form a difference test.

Now assume that $X \in [\sigma] \cap Q$ and $\Phi^X = A$. Hirschfeldt, Nies and Stephan showed that because $A$ is not $K$-trivial, it is not a base for randomness. In other words, no set that is Martin-Löf random relative to $A$ can compute $A$, so $X$ is not random relative to $A$. Therefore, $X \in U_n[A] = U_n[\Phi|^X]$ for all $n$. This shows that $X \in \bigcap_{n \in \omega} V_n \cap [\sigma] \cap Q$, so $X$ is not difference random. Hence the claim is satisfied by taking $\tau = \sigma$.

3. Effectivizing the Forcing

In this section we give a construction of a $\Delta^0_2$ set with properties (1), (2) and (3).

This construction is an effectivization of the forcing approach. It is conceptually similar to Sacks’s construction of a $\Delta^0_2$ minimal degree, which can be seen as an effectivization of Spector’s minimal degree construction.

Theorem 3.1. There is a $\Delta^0_2$ set with properties (1), (2) and (3).

Proof. Using $\emptyset'$ as an oracle we will define a sequence of conditions $\langle p_i : i \in \omega \rangle$ in the partial order $\mathbb{P}$. If $p_i = \langle \tau, Q \rangle$ and $p_{i+1} = \langle \sigma, R \rangle$ we will ensure that $\sigma \succ \tau$. However, we will not require that $R \subseteq Q$. Essentially, our oracle construction can make incorrect guesses as to which $\Pi^0_1$ classes to use, provided that a correct guess is made eventually. We will define $p_s$ at stage $s$ of the construction. Additionally at stage $s$ we will define $a_s$ to be a finite sequence of triples $\langle Q, \sigma, \varepsilon \rangle$ where $Q$ is a $\Pi^0_1$ class, $\sigma \in 2^{<\omega}$, and $\varepsilon$ is a rational. The sequence $a_s$ will be used to recover information about previous stages in the construction. We let $l(a_s)$ be the length of the sequence $a_s$ and we define partial functions $Q, \sigma$ and $\varepsilon$ such that if $e < l(a_s)$ then $\langle Q(e), \sigma(e), \varepsilon(e, e) \rangle$ is the $e$th element of $a_s$. We shall maintain the following construction invariants for all stages $s$:

(i) If $i < j < l(a_s)$, then $Q(s, j) \subseteq Q(s, i)^{\varepsilon(s, i)}$ and $\sigma(s, i) \preceq \sigma(s, j)$.

(ii) If $p_s = \langle \tau, R \rangle$ and $i < l(a_s)$ then $R \subseteq Q(s, i)^{\varepsilon(s, i)}$ and $\sigma(s, i) \preceq \tau$.

The construction is as follows. Let $\langle S_e : e \in \omega \rangle$ enumerate all $\Pi^0_1$ classes. At stage 0, let $p_0 = \lambda \langle \lambda, P \rangle$ and let $a_0$ be the empty sequence. Our construction invariants hold trivially.

At stage $s + 1$, given $p_s = \langle \tau, Q \rangle$, we use $\emptyset'$ to find a condition $\langle \sigma, Q \rangle$ such that $\sigma$ is a strict extension of $\tau$, and $\mu_\sigma(P) < 1/2$. Claim 2.4 established that such a condition exists, and as the value of $\mu_\sigma(P)$ is computable in $\emptyset'$ we can simply
search for a suitable $\sigma$. At this point we ask the following question. Does there exist $e < l(a_s)$ and $\nu$ such that

\[(\tau \preceq \nu \preceq \sigma) \land ([\tau] \cap S_{e} \neq \emptyset) \land (\mu_{\nu}(S_{e}) < \varepsilon(s, e))\]

If not, then we define $p_{s+1} = \langle \sigma, Q_{1} \rangle$ where $\varepsilon_{s+1}$ is chosen to make $p_{s+1}$ a condition. It follows from the proof of Claim 2.3 that $\varepsilon_{s+1}$ can simply be chosen to be strictly less than $\min\{\mu_{\nu}(Q_{s}), 1/2 - \sum_{i \leq s} \varepsilon_{i}\}$. Define $a_{s+1}$ to be the sequence obtained by appending $\langle Q_{s}, \sigma, \varepsilon_{s+1} \rangle$ to the end of $a_{s}$. Note that the construction invariants are maintained.

If (3.1) holds for some suitable $e$ and $\nu$, then choose some $e$ and $\nu$ such that $e$ is minimal. Our construction invariants ensure that $Q_{s} \subseteq Q(s, e)_{\sigma(s, e)}$ and $\nu \geq \tau \geq \sigma(s, e)$. This implies that $\mu_{\nu}(Q(s, e)) \geq \varepsilon(s, e)$. Therefore there is some $\xi \supseteq Q(s, e) \neq \emptyset$ and $[\xi] \cap S_{e} = \emptyset$. Define $p_{s+1} = \langle \xi, Q_{s}, e \rangle$ and define $a_{s+1} = a_{s} \cup e$. Observe that construction invariant (i) is maintained because $a_{s+1}$ is a subsequence of $a_{s}$, and construction invariant (ii) is maintained because construction invariant (i) held at stage $s$. This ends the construction.

Let $X = \bigcup \{\tau: (\exists s) \ p_{s} = \langle \tau, Q \rangle\}$. To verify that $X$ has the desired properties, we first show that $\lim_{s} l(a_{s}) = \infty$. Assume that for some $s_{0}$, for all $s \geq s_{0}$, $l(a_{s}) \geq e$. Assume at some stage $s_{1} > s_{0}$, we have that $l(a_{s}) = e$. This can only occur because (3.1) held for $e$, and $e$ was the least such value for which it held. Hence if $\langle \tau, Q \rangle = p_{s_{1}}$ then $[\tau] \cap S_{e} = \emptyset$. This implies that (3.1) will never again hold for $e$ and hence for all $s > s_{1}$, $l(a_{s}) \geq e + 1$.

If $l(a_{s+1}) > l(a_{s})$, then condition (3.1) does not hold. Hence as $\lim_{s} l(a_{s}) = \infty$, for infinitely many stages $s$, condition (3.1) does not hold. This implies that $X$ has infinite length, hence is a Martin-Löf random set, and $\rho(P \mid X) \leq 1/2$. Now assume that for some $e$, $X \in S_{e}$. Let $s_{0}$ be a stage such that for all $s \geq s_{0}$, $l(a_{s}) > e$. Let $\langle \tau, Q \rangle = p_{s_{0}}$. It must be that for any finite string $\nu$ such that $\tau \preceq \nu \prec \sigma$, $\mu_{\nu}(S_{e}) > \varepsilon(s_{0}, e)$ because for all $s \geq s_{0}$ we know that condition (3.1) does not hold for $e$. Hence $\rho(S_{e} \mid X) > 0$. 

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