Diametric Colorings in Ultrametric Spaces

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Abstract. Let Γ_X denote the family of compact subsets of (X, d). A coloring $\chi : \Gamma_X \to [k]$ is *diametric* if every pair of compact subsets with equal diameters receive the same color. A free ultrafilter $\mathcal{F}$ is called *diametrically Ramsey* if every diametric coloring admits a set $A \in \mathcal{F}$ whose compact subsets are monochrome. We show that every infinite ultrametric space contains a sequence (x_n) so that every free ultrafilter containing (x_n) is diametrically Ramsey, extending a result of Prostatov and Prostatova [1].

1. Introduction

Ramsey Theory explores the underlying structure emerging in "large enough" complex systems. For example, Frank Ramsey [1] proved that for each $k \in \mathbb{N}$ there is a sufficiently large $n \in \mathbb{N}$ such that in any red-blue coloring of the edges of the complete graph K_n there is a set of k vertices joined by edges of the same color.

Another seminal result is Van der Waerden's theorem, which states that for all positive integers $r, k \in \mathbb{N}$, there is a large enough $n \in \mathbb{N}$ such that if we color the integers in $[n] \coloneqq \{1, 2, \ldots, n\}$ using k colors, one can always find a set of r monochromatic integers in arithmetic progression [2].

Motivated by these kinds of classical results, we study the structural properties of infinite spaces using a Ramsey-theoretic lens. In particular, we will color a class of subsets of the space and search for an infinite set whose subsets in this class receive the same color. We formalize this as follows.

Fix an infinite metric space (X, d) and let $k \in \mathbb{N}$ be a postive integer. For a family $\mathcal{A}$ of subsets of X, a *k-coloring* of $\mathcal{A}$ is any mapping $\chi : \mathcal{A} \to [k]$. We would like to find a set $M \subseteq X$ and a color $c \in [k]$ such that $\chi(N) = c$ for every subset $N \subseteq M$ with $N \in \mathcal{A}$. In this case, we say that M is *monochrome*.

In this context, the "large" objects in X which we will work with are free ultrafilters [4]. A *filter* $\mathcal{F}$ on X is a collection of subsets of X satisfying the following for all subsets $A, B \subseteq X$:

(1) If $A \in \mathcal{F}$ and $A \subseteq B$ then $B \in \mathcal{F}$;

(2) If $A, B \in \mathcal{F}$ then $A \cap B \in \mathcal{F}$;
(3) $\emptyset \notin \mathcal{F}$ and $X \in \mathcal{F}$.

A filter $\mathcal{F}$ is called an *ultrafilter* if it is not properly contained in a filter on X. A filter $\mathcal{F}$ is called *free* if $\bigcap \mathcal{F} = \emptyset$. Hence free filters are "spread out" throughout the space and ultrafilters are maximal filters, so we consider *free ultrafilters* as "large" objects in X.

Given that these are the large objects in focus, it is natural to ask whether there is a free ultrafilter $\mathcal{F}$ such that for every coloring of the r-element subsets of X there is a monochrome set $M \in \mathcal{F}$. It turns out that this question is undecidable in ZFC even with $X = \mathbb{N}$, though the statement is true if we accept continuum hypothesis [5]. Hence we must define more restrictive classes of colorings.

To this end, (authors) introduce the following [3]. A coloring $\chi : [X]^2 \to \{0, 1\}$ of the two-element subsets of X is called *isometric* if $\chi(\{x_1, y_1\}) = \chi(\{x_2, y_2\})$ whenever $d(x_1, y_1) = d(x_2, y_2)$. A free ultrafilter $\mathcal{F}$ is called *metrically Ramsey* if for every isometric coloring of $[X]^2$ there is a monochrome set $M \in \mathcal{F}$.

It turns out that in the particular case of ultrametric spaces, metrically Ramsey free ultrafilters are not too hard to construct. Recall that an *ultrametric* d on a set X is a metric satisfying the *strong triangle inequality*: for all $x, y, z \in X$

$$d(x, y) \leq \max\{d(x, z), d(z, y)\}.$$

(Authors) leverage the properties of the ultrametric to prove the following theorem.

Theorem 1.1. *Fix an infinite ultrametric space X. There is a sequence (x_n) in X such that every free ultrafilter $\mathcal{F}$ containing (x_n) is metrically Ramsey.*

As a follow up, one may ask if similar structure exists when coloring a larger class of subsets of X. The positive answer to this question is the keynote of this paper. In this connection, we will analyze the family Γ_X of all compact subsets of X.

We generalize isometric colorings along these lines. The map $\chi : \Gamma_X \to [k]$ is called a *diametric coloring* if $\chi(A_1) = \chi(A_2)$ for every pair A_1, A_2 of compact subsets of X with $\operatorname{diam} A_1 = \operatorname{diam} A_2$. Hence, a subset $M \subseteq X$ is monochrome if its compact subsets receive the same color.

Given this, we say that a free ultrafilter $\mathcal{F}$ on X is *diametrically Ramsey* if for every diametric coloring χ there is a monochrome set $M \in \mathcal{F}$. Since finite sets are compact, Γ_X contains $[X]^2$ so that every diametric coloring is isometric.

In this context, our main result is the following.

Theorem 1.2. *Fix an infinite ultrametric space X. There is a sequence (x_n) in X such that every free ultrafilter $\mathcal{F}$ containing (x_n) is diametrically Ramsey.*

Building towards (theorem), the following two sections review some elementary properties of ultrametric spaces and filters. We then prove the main result in (section).

2. Ultrametric Analysis

In this short section, we provide some interesting examples of ultrametric spaces and survey some of their fundamental properties.

2.1. **Examples: The space $\mathbb{N}^{\mathbb{N}}$, graphs, and ε-chains.** The simplest example of an ultrametric on a set X is the discrete metric d, where $d(x, y)$ is 1 if $x \neq y$ and 0 otherwise. Another simple example is $(\mathbb{N}, d)$, where $d(n, m) = \max\{1 + 1/n, 1 + 1/m\}$ if $n \neq m$ and $d(n, m) = 0$ otherwise. This metric was first constructed by (guy) in (year) to (task) [3].

However, there are much more interesting constructions. In this regard, we will construct ultrametrics on the Baire space $\mathbb{N}^{\mathbb{N}}$, connected graphs, and general uniformly disconnected metric spaces.

2.1.1. *The Baire space.* We will first discuss the *Baire space* $\mathbb{N}^{\mathbb{N}}$, which is the space of all sequences of natural numbers.

For two distinct sequences $x = (x_n)$, $y = (y_n)$ in $\mathbb{N}$, we define $m(x, y) = \min\{k \in \mathbb{N} : x_k \neq y_k\}$ to be the first index at which x and y do not coincide. For distinct sequences $x, y \in \mathbb{N}^{\mathbb{N}}$, set $d(x, y) = m(x, y)^{-1}$ with $d(x, y) = 0$ if $x = y$. Then d is an ultrametric on $\mathbb{N}^{\mathbb{N}}$.

Proof. The symmetry and non-negativity of d is immediate. Furthermore, $d(x, x) = 0$ by definition, and if $d(x, y) = 0$ then we must have $x = y$ since $m(x, y) \geq 1$. To prove the strong triangle inequality for d, fix $x, y, z \in \mathbb{N}^{\mathbb{N}}$. We assume x, y, z are all distinct sequences as the result is immediate otherwise. Observe that

$$\begin{aligned}
&d(x, y) \leq \max\{d(x, z), d(z, y)\} \\
&\Leftrightarrow m(x, y)^{-1} \leq \max\{m(x, z)^{-1}, m(z, y)^{-1}\} \\
&\Leftrightarrow m(x, y)^{-1} \leq \min\{m(x, z), m(z, y)\}^{-1} \\
&\Leftrightarrow m(x, y) \geq \min\{m(x, z), m(z, y)\}.
\end{aligned}$$

Clearly $m(x, y) \geq \min\{m(x, z), m(z, y)\}$: if $\ell = m(x, y)$ then for each $k \in \{1, 2, \ldots, \ell - 1\}$ the terms $x_k = y_k$, so if $m(x, z) \geq \ell + 1$ and

$m(z,y) \geq \ell+1$ then $x_\ell = z_\ell = y_\ell$ so that $m(x,y) \geq \ell+1$ is a contradiction. Therefore, d is an ultrametric. □

2.1.2. *Graphs.* (the following is due to (author), with intuition, ...) Let G be a connected graph with positive edge-weights. For an edge e in G, let $w(e)$ denote its weight. Given a walk $x = (v_1, v_2, \ldots, v_n)$ in G, we will denote by e_x an edge in the walk with maximum weight.

We say that a walk x between two vertices u, v is a *minimax walk* if there is no other walk x' between u, v whose max-weight edge is lighter than e_x. Equivalently, $w(e_x) \leq w(e_{x'})$ for every walk x' between u, v.

We can use this notion to define an ultrametric on $V(G)$. Specifically, given two distinct vertices $u, v \in V(G)$ with minimax walk x, we set $\ell(u,v) = w(e_x)$, with $\ell(u,u) = 0$. The proof that ℓ is an ultrametric is as follows.

Proof. That ℓ is symmetric and non-negative is immediate. By definition, $\ell(u,u) = 0$ and if $\ell(u,v) = 0$ then $u = v$, as otherwise there is an edge in G with weight 0 even though its edges have only positive weights.

To prove the ultrametric inequality, fix $u, v, w \in V(G)$. We may assume that u, v, w are distinct as otherwise the claim is immediate. Let $x_{u,w} = (v_1, v_2, \ldots, v_m)$ and $x_{w,v} = (v_m, v_{m+1}, \ldots, v_n)$ denote minimax walks between u, w and w, v respectively, and let $x = (v_1, v_2, \ldots, v_n)$ be their union. Then the max-weight edge in x has weight $\max\{\ell(u,w), \ell(w,v)\}$. Since x is a walk between u, v, we have $\ell(u,v) \leq \max\{\ell(u,w), \ell(w,v)\}$, completing the proof. □

2.1.3. *Uniformly disconnected spaces.* (cite def) Let (X,d) be any metric space and $\varepsilon > 0$ be given. An *ε-chain* between the pair x, y of distinct points in X is a finite sequence $x = x_0, x_1, \ldots, x_n = y$ such that

$$\max_{1 \leq i \leq n} d(x_{i-1}, x_i) \leq \varepsilon \cdot d(x,y).$$

In this case, we say that x, y are ε-connected. Observe that if x, y are ε-connected then they are ε'-connected for every $\varepsilon' \geq \varepsilon$; and if x, y can not be ε-connected then they can not be ε'-connected for every $\varepsilon' \leq \varepsilon$.

The space X is called *uniformly disconnected* if there is an $\varepsilon > 0$ such that no two points in X can be ε-connected. It is not hard to prove that uniform disconnectivity is stronger than total disconnectivity. To give some intuition, we note that the Cantor set $\mathcal{C}$ is uniformly disconnected and the set $\{1/n : n \in \mathbb{N}\}$ is not [tb].

Let (X,d) be a uniformly disconnected metric space. For $x, y \in X$, let $c(x,y)$ be the infimum over all $\varepsilon > 0$ such that x and y are $d(x,y)^{-1} \cdot \varepsilon$-connected. Then c is an ultrametric on X.

Proof. Clearly c is symmetric and non-negative. If $x = y$ then clearly x, y are ε-connected for every $\varepsilon > 0$ so that $c(x, y) = 0$. On the other hand, if $c(x, y) = 0$ then $x = y$, otherwise for each $\varepsilon > 0$ the points x, y are ε-connected, so X is not uniformly disconnected, a contradiction.

The last thing to prove is the strong triangle inequality for c. To this end, fix $x, y, z \in X$ and let $\varepsilon > 0$ be given. We may assume the points x, y, z are distinct, otherwise the claim is immediate.

By definition of the infimum, there exist $\gamma_1, \gamma_2 > 0$ with $\gamma_1 \leq c(x, z) + \varepsilon$ and $\gamma_2 \leq c(z, y) + \varepsilon$ such that x, z are $d(x, z)^{-1} \cdot \gamma_1$-connected and z, y are $d(z, y)^{-1} \cdot \gamma_2$-connected. Hence we obtain sequences

- $x = x_0, x_1, \ldots x_m = z$ with $\max_{1 \leq i \leq m} d(x_{i-1}, x_i) \leq \gamma_1$; and
- $z = x_m, x_{m+1}, \ldots, x_n = y$ with $\max_{m+1 \leq i \leq n} d(x_{i-1}, x_i) \leq \gamma_2$.

Now set $\gamma = \max\{\gamma_1, \gamma_2\}$ and observe that x, y are γ-connected since

$$\max_{1 \leq i \leq n} d(x_{i-1}, x_i) \leq \gamma = \frac{\gamma}{d(x, y)} \cdot d(x, y).$$

Then we obtain

$$\begin{aligned} c(x, y) \leq \gamma &= \max\{\gamma_1, \gamma_2\} \\ &\leq \max\{c(x, z) + \varepsilon, c(z, y) + \varepsilon\} \\ &= \max\{c(x, z), c(z, y)\} + \varepsilon, \end{aligned}$$

so sending $\varepsilon \to 0$ yields $c(x, y) \leq \max\{c(x, z), c(z, y)\}$. □

2.2. **Properties of ultrametric spaces.** The strong triangle inequality is much stronger than the usual triangle inequality. Because of this, ultrametric spaces have some elegant properties which we explore now.

First, it turns out that every triangle is isosceles.

Lemma 2.1. *If x, y, z are distinct points in an ultrametric space X and $d(x, y) < d(y, z)$ then $d(y, z) = d(x, z)$.*

Proof. Note that d is an ultrametric and $d(x, y) < d(y, z)$ so that

$$d(x, z) \leq \max\{d(x, y), d(y, z)\} = d(y, z),$$

and since $d(y, z) > d(x, y)$, we have $d(x, y) < d(x, z)$ as otherwise

$$d(y, z) \leq \max\{d(y, x), d(x, z)\} = \max\{d(x, y), d(x, z)\} = d(x, y)$$

is a contradiction. Thus $d(y, z) \leq \max\{d(x, y), d(x, z)\} = d(x, z)$. Combining everything together, we obtain $d(y, z) = d(x, z)$. □

We now examine open balls in ultrametric spaces. An *open ball* (or simply a ball) of radius $\varepsilon > 0$ centered about a point $x \in X$ is the set

$$B_\varepsilon(x) \coloneqq \{y \in X : d(x, y) < \varepsilon\}.$$

A subset $\mathcal{O}$ of X is called *open* if it can be written as a union of open balls. A set is *closed* if its complement is open.

Open balls in ultrametric spaces have vastly unintuitive properties. For example, every point in a ball is its center.

Lemma 2.2. *Let $B_\varepsilon(x)$ be an open ball in X. Then $B_\varepsilon(x) = B_\varepsilon(y)$ for every point $y \in B_\varepsilon(x)$.*

Proof. Fix $y \in B_\varepsilon(x)$ so that $d(x, y) < \varepsilon$. If $t \in B_\varepsilon(y)$ then $d(y, t) < \varepsilon$. Then $t \in B_\varepsilon(x)$ since

$$d(x, t) \le \max\{d(x, y), d(y, t)\} < \varepsilon.$$

The reverse inclusion follows symmetrically as $x \in B_\varepsilon(y)$. $\square$

Another important result is that if two balls intersect then one of them contains the other. More generally, we have the following lemma.

Lemma 2.3. *Fix $\varepsilon_1, \varepsilon_2 > 0$ and $x, y \in X$. If $B_{\varepsilon_1}(x) \cap B_{\varepsilon_2}(y) \neq \emptyset$ then $B_{\varepsilon_1}(x) \subseteq B_{\varepsilon_2}(y)$ or $B_{\varepsilon_2}(y) \subseteq B_{\varepsilon_1}(x)$. (That is, two balls are either disjoint or one of them contains the other.)*

Proof. Assume without loss of generality that $\varepsilon_1 \le \varepsilon_2$. If $B_{\varepsilon_1}(x) \cap B_{\varepsilon_2}(y) \neq \emptyset$, there is a point $t \in X$ with $t \in B_{\varepsilon_1}(x)$ and $t \in B_{\varepsilon_2}(y)$. By (lemma) and since $\varepsilon_1 \le \varepsilon_2$, we obtain $B_{\varepsilon_1}(x) = B_{\varepsilon_1}(t) \subseteq B_{\varepsilon_2}(t) = B_{\varepsilon_2}(y)$ as required. $\square$

A generalization of (lemma) is as follows.

Lemma 2.4. *Let $A \subseteq X$ and consider any ball $B_\varepsilon(x)$ in X. If $B_\varepsilon(x)$ meets A then $A \cap B_\varepsilon(x)$ is a ball in the space (A, d).*

Proof. Since $A \cap B_\varepsilon(x) \neq \emptyset$, there is a point $a \in A \cap B_\varepsilon(x)$. Let $B_A = \{t \in A : d(t, a) < \varepsilon\}$ be a ball in A. We show that $A \cap B_\varepsilon(x) = B_A$.

Note from (lemma) that a is the center of $B_\varepsilon(x)$ so that $A \cap B_\varepsilon(x) = A \cap B_\varepsilon(a)$. Then if $t \in A \cap B_\varepsilon(x)$ we have $t \in A \cap B_\varepsilon(a)$ so that $d(t, a) < \varepsilon$ and hence $t \in B_A$. On the other hand, if $t \in B_A$ then from the strong triangle inequality we obtain

$$d(x, t) \le \max\{d(x, a), d(a, t)\} < \varepsilon,$$

since $a \in B_\varepsilon(x)$. Hence, $t \in A \cap B_\varepsilon(x)$ completes the proof. $\square$

Furthermore, it turns out that all open balls are also closed in X.

Lemma 2.5. *If $B_\varepsilon(x)$ is an open ball in X, then $X \setminus B_\varepsilon(x)$ is closed.*

Proof. Suppose for a contradiction that there is a point $t \in X \setminus B_\varepsilon(x)$ such that for every $r > 0$ the ball $B_r(t)$ is not contained in $X \setminus B_\varepsilon(x)$, so $B_r(t) \cap B_\varepsilon(x) \neq \emptyset$. Setting $r = \varepsilon$ and using (lemma), we have $B_\varepsilon(t) \subseteq B_\varepsilon(x)$ or $B_\varepsilon(t) \subseteq B_\varepsilon(x)$. In either case, (lemma) implies equality. But then $t \in X \setminus B_\varepsilon(x) = X \setminus B_\varepsilon(t)$ is a contradiction. Hence $X \setminus B_\varepsilon(x)$ is a union of open balls so that $B_\varepsilon(x)$ is closed in X. $\square$

Our final application of the ultrametric inequality is to the diameter of subsets of the space.

Lemma 2.6. *Let $A \subseteq X$ be non-empty with $a \in A$. Then* $\operatorname{diam} A = \sup\{d(a,x) : x \in A\}$.

Proof. Set $u = \sup\{d(a,x) : x \in A\}$ and fix $x, y \in A$. Then

$$d(x,y) \leq \max\{d(x,a), d(a,y)\} = \max\{d(a,x), d(a,y)\} \leq u$$

so that u is an upper bound of $D = \{d(x,y) : x, y \in A\}$. Since $u = \sup\{d(a,x) : x \in A\}$, for any given $\varepsilon > 0$, there exists a point $x_\varepsilon \in A$ with $u \leq d(a,x_\varepsilon)+\varepsilon$. But $a, x_\varepsilon \in A$ so that $u = \sup D = \operatorname{diam} A$ which completes the proof. $\square$

3. Filters

In this short section, we introduce a sequence of lemmas building up to (lemma), which is fundamental to the proof of the main result. Recall from the introduction that a *filter* $\mathcal{F}$ on X is a family of subsets of X with $\emptyset \notin \mathcal{F}$, $X \in \mathcal{F}$, and which is closed under the superset inclusion and finite intersections.

A filter $\mathcal{F}$ is an *ultrafilter* if it is not properly contained in another filter, and we call $\mathcal{F}$ *free* if $\bigcap \mathcal{F} = \emptyset$. We say that $\mathcal{F}$ has the *finite intersection property* (FIP) if the intersection of any finite number of sets in $\mathcal{F}$ is non-empty.

The first lemma is the following.

Lemma 3.1. *If $\mathcal{K}$ is a family of subsets satisfying the FIP, then there is a filter $\mathcal{F}$ containing each element of $\mathcal{K}$.*

Proof. First let $\mathcal{F}' = \mathcal{K} \cup \mathcal{I}$, where $\mathcal{I}$ is the set of all finite intersections of elements of $\mathcal{K}$. Hence $\mathcal{F}'$ is closed under finite intersections. Then, let $\mathcal{F} = \mathcal{F}' \cup \mathcal{S}$, where $A \in \mathcal{S}$ if and only if A contains a set in $\mathcal{F}'$.

Clearly $\mathcal{F}$ is closed when taking supersets. If $A, B \in \mathcal{F}$, the only non-trivial needing consideration is, without loss of generality, when $A \in \mathcal{S}$. So, if $B \in \mathcal{S}$ or $B \in \mathcal{F}'$, then there exist sets $A', B' \in \mathcal{F}'$ such that $A' \subseteq A$ and $B' \subseteq B$ (if $B \in \mathcal{F}'$ then $B' = B$). Since $\mathcal{F}'$ is closed under finite intersections, $A' \cap B' \in \mathcal{F}'$. Then, from $A' \cap B' \subseteq A \cap B$ it follows that $A \cap B \in \mathcal{S} \subseteq \mathcal{F}$. Hence $\mathcal{F}$ is closed under finite intersections. $\square$

Lemma 3.2. *A family $\mathcal{F}$ is an ultrafilter if and only if for every subset $A \subseteq \mathbb{N}$ either $A \in \mathcal{F}$ or $A^c \in \mathcal{F}$.*

Proof. Let $\mathcal{F}$ be an ultrafilter and suppose for a contradiction that there is a subset $A \subseteq \mathbb{N}$ with $A, A^c \notin \mathcal{F}$. So every set in $\mathcal{F}$ intersects both A and A^c. It follows from (lemma) that the filter extending $\mathcal{F} \cup \{A, A^c\}$ properly contains $\mathcal{F}$, which is a contradiction. Now suppose $\mathcal{F}$ is a filter such that for every subset $A \subseteq \mathbb{N}$, either $A \in \mathcal{F}$ or $A^c \in \mathcal{F}$. Assume for a contradiction that $\mathcal{F}'$ is a filter which properly contains $\mathcal{F}$. So there is a subset $E \subseteq \mathbb{N}$ with $E \in \mathcal{F}'$ and $E \notin \mathcal{F}$. Thus $E^c \in \mathcal{F}$ and hence $E^c \in \mathcal{F}'$. But then $\mathcal{F}'$ contains the emptyset since it is closed under finite intersections and $\emptyset = E \cap E^c \in \mathcal{F}'$, a contradiction. □

Lemma 3.3. *A family $\mathcal{F}$ is an ultrafilter if and only if $\mathcal{F}$ has the Ramsey property.*

Proof. Let $\mathcal{F}$ be an ultrafilter and suppose for a contradiction that $A = A_1 \cup A_2$ is in $\mathcal{F}$ but $A_1, A_2 \notin \mathcal{F}$. Hence (lemma) we have $A_1^c, A_2^c \in \mathcal{F}$ so that $A^c = A_1^c \cap A_2^c \in \mathcal{F}$. Consequently, $\emptyset = A \cap A^c \in \mathcal{F}$ is a contradiction. The case where $A = A_1 \cup \cdots \cup A_n$ follows via elementary induction. Conversely, assume $\mathcal{F}$ has the Ramsey property. If $\mathcal{F}$ is not an ultrafilter, then there is a subset $A \subseteq \mathbb{N}$ with $A, A^c \notin \mathcal{F}$. But $\mathbb{N} \in \mathcal{F}$ and $\mathbb{N} = A \cup A^c$, so we must have $A \in \mathcal{F}$ or $A^c \in \mathcal{F}$, a contradiction. □

4. Main Result

4.1. **A technical lemma.** (authors) introduce the following lemma, contructing a sequence (x_n) with a unique property. We then use this sequence to prove the main result. Hence, for the sake of completeness, we start this section with its statement and proof.

Lemma 4.1. *Let (X, d) be an infinite metric space. Then there is a sequence $\{x_n\}_{n=1}^{\infty}$ of distinct points in X such that either*

(1) The sequence $\{d(x_1, x_n)\}_{n=1}^{\infty}$ is strictly monotone; or
(2) For every $n \in \mathbb{N}$ and $i, j \geq n$ the distances $d(x_n, x_i) = d(x_n, x_j)$.

Proof. We first assume that there is a point $x_0 \in X$ such that $d(x_0, X) \coloneqq \{d(x_1, x_n) : x_n \in X\}$ is not finite. Hence, there is a countably infinite subset $E \subseteq X$ with $x_0 \notin E$ and $d(x_0, x) \neq d(x_0, y)$ for every $x, y \in E$. We obtain from E the sequence $\xi = \{d(x_0, x) : x \in E\}$. Since ξ is a sequence of reals, it has a monotone subsequence $\{d(x_0, x_n)\}_{n=1}^{\infty}$ whose points are distinct by construction of E. Since d is a metric, $x_i \neq x_j$ for every $i, j \in \mathbb{N}$ and so $\{x_n\}_{n=1}^{\infty}$ is the desired sequence.

Otherwise, $d(x, X)$ is finite for every $x \in X$. Fix $x_0 \in X$ and assume without loss of generality that $\ell_1 \in d(x_0, X)$ is non-zero. Let E_1 be a countable subset of X with $E_1 \subseteq \{x \in X : d(x_0, x) = \ell_1\}$. Choose $x_1 \in E_1$, and note that $d(x_0, E_1) = \{\ell_1\}$ is a singleton set and $x_0 \notin E_1$.

For $n \geq 2$, we choose x_n and define E_n inductively as follows. As above, let $\ell_n \in d(x_{n-1}, X)$ be non-zero and let E_n be a countable subset of X with $E_n \subseteq \{x \in X : d(x_{n-1}, x) = \ell_n\}$. Again, we choose $x_n \in E_n$ and observe that $d(x_{n-1}, E_n) = \{\ell_n\}$. Continuing this way, we obtain the sequence from (2). □

4.2. **Main result.** Recall that the map $\chi : \Gamma_X \to [k]$ is called a *diametric coloring* if $\chi(A_1) = \chi(A_2)$ for every pair A_1, A_2 of compact subsets of X with $\operatorname{diam} A_1 = \operatorname{diam} A_2$. A subset A of X is called *monochrome* if its compact subsets receive the same color; that is, there is a color $\varphi \in [k]$ such that $\chi(\Gamma_A) = \{\varphi\}$. A free ultrafilter $\mathcal{F}$ on X is called *diametrically Ramsey* if for every diametric coloring χ there is a monochrome set $A \in \mathcal{F}$.

We are ready to prove the main result.

Theorem 4.1. *Fix an infinite ultrametric space X. There is a sequence (x_n) in X such that every free ultrafilter $\mathcal{F}$ containing (x_n) is diametrically Ramsey.*

Proof. Let χ be any diametric coloring on X and fix a free ultrafilter $\mathcal{F}$ containing the sequence (x_n) as obtained in (lemma).

Let $h : (x_n) \to \mathbb{R}^+$ be a fixed map. How we define h depends on (x_n), so we proceed in this regard later on. Moreover, suppose $f : \mathbb{R}^+ \to [k]$ is any mapping satisfying $f(h(x_n)) = \chi(A)$ whenever $A \in \Gamma_X$ is a compact subset of X with $\operatorname{diam} A = h(x_n)$. Finally, we set $c = f \circ h$.

Write $(x_n) = c^{-1}([k]) = \cup_{j=1}^{k} c^{-1}(\{j\})$ and observe that since $E \in \mathcal{F}$, (lemma) implies that there is a color $\varphi \in [k]$ with $c^{-1}(\{\varphi\}) \in \mathcal{F}$. We set $A = c^{-1}(\{\varphi\})$ and complete the proof by showing that A is monochrome. Specifically, we show that if K is a compact subset of A then $\chi(K) = \varphi$. So fix such a set K.

Since K is compact, there are points $x_i, x_j \in K$ with $i < j$ and $d(x_i, x_j) = \operatorname{diam} K$, applying (lemma). We now consider the conditions on (x_n) as described in (lemma), and define h accordingly to complete the proof.

Case 1. We will first assume that case (1) of (lemma) holds, namely that (x_n) is a sequence of distinct points in X where $\{d(x_0, x_n)\}_{n=1}^{\infty}$ is strictly monotone for some point $x_0 \in X$. In this case, h will indicate the distance to x_0 from a term $x_n \in E$, given by $h(x_n) = d(x_0, x_n)$.

If h is strictly increasing, then we have $d(x_0, x_i) < d(x_0, x_j)$. Hence (lemma) implies that $d(x_i, x_j) = d(x_0, x_j)$, since d is an ultrametric. Otherwise $d(x_0, x_i) > d(x_0, x_j)$ so that $d(x_i, x_j) = d(x_0, x_i)$ using (lemma) once more. Possibly swapping the symbols i, j, we assume the latter case holds. Since χ is diametric, $x_j \in A$, and $\operatorname{diam} K =$

$d(x_i, x_j) = d(x_0, x_j)$, we have

$$c(x_j) = f(d(x_0, x_j)) = \chi(K) = \varphi,$$

as needed.

Case 2. We now assume that case (2) of (lemma) applies to (x_n). Namely, for each $n \in \mathbb{N}$ and $i, j \geq n$ we have $d(x_n, x_i) = d(x_n, x_j)$. Define $h : E \to \mathbb{R}^+$ by $h(x_n) = d(x_n, x_{n+1})$, and note that $h(x_n) = d(x_n, x_j)$ for every $j > n$. Again, since χ is diametric and $i < j$, we have $h(x_i) = d(x_i, x_j)$ and, as desired,

$$c(x_i) = f(d(x_i, x_j)) = \chi(K) = \varphi.$$

This completes the proof, since A is χ-monochrome in both cases. $\square$

Acknowledgements. I would like to extend my deepest thanks to my Directed Reading Program (DRP) advisor, Aaron Shalev, for his invaluable guidance and support. His expertise, dedication, and insightful feedback have not only strengthened this work substantially, but they have also deepened my understanding of the subject.

I would also like to thank the DRP commitee for their significant efforts in organizing the program and fostering an environment that encourages rigorous academic inquiry and growth. Their collective efforts have provided me with a unique opportunity to engage thoroughly with my area of study, for which I am incredibly grateful.