

APPLICATIONS OF THE MAGIDOR ITERATION TO ULTRAFILTER THEORY

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ABSTRACT. We characterize sums of normal ultrafilters after the Magidor iteration of Prikry forcings over a discrete set of measurable cardinals. We apply this to show that the weak Ultrapower Axiom is not equivalent to the Ultrapower Axiom. We also construct a non-rigid ultrapower and two uniform ultrafilters on different cardinals that have the same ultrapower.

1. INTRODUCTION

Iterated Prikry forcing was first introduced by Magidor [11] in his seminal “*study on identity crises*” to produce a model of ZFC in which the least measurable cardinal is strongly compact. The rough idea is to iteratively singularize each cardinal α in some set of measurable cardinals Δ using the Prikry forcing associated with a normal measure on α .

Ben-Neria [1] was the first to notice that if Magidor’s construction is carried out over the core model K , then the normal ultrafilters of the forcing extension can be classified in terms of the normal ultrafilters of K . Recently, Ben-Neria’s work was substantially extended and generalized by Kaplan [9], who showed, most significantly, that the classification could be carried out even when the ground model is not the core model.

This paper is focused on the special case of Magidor’s construction in which the set of measurable cardinals Δ to be singularized is *discrete* in the sense that it does not contain any of its limit points. In this restricted setting, the forcing can be viewed as a product of Prikry forcings which we will refer to as the *Magidor product*. For discrete Magidor products, Kaplan’s theorem can be stated as follows:

Theorem 1.1 (Kaplan). *Suppose G is V -generic for a Magidor product of Prikry forcings on a discrete set $\Delta \subseteq \kappa$. Then every normal measure U on κ in V generates a normal ultrafilter U^* in $V[G]$. Moreover $j_{U^*} \restriction V = i \circ j_U$, where i is an iterated ultrapower of V_U .*

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Here and below,

$$j_U : V \rightarrow V_U$$

denotes the ultrapower of the universe of sets by U .

This paper addresses the question of whether Theorem 1.1 can be generalized to ultrafilters U that are not normal. Although we do prove a slight generalization of Kaplan's result to a collection of measures we call *mild* (see 3.8), the more surprising contribution of this paper is a negative answer to the general question: we show in Section 4 that in the context of Theorem 1.1, a κ -complete ultrafilter U on κ can extend in unexpected ways after a Magidor product of Prikry forcings. In particular, the filter generated by U in the forcing extension is not an ultrafilter. Moreover, these unexpected extensions answer several natural questions in the theory of ultrafilters.

For example, recall that Kunen's inconsistency theorem states that there is no nontrivial elementary embedding from the universe of sets to itself. Suppose U is a countably complete ultrafilter, and let V_U be the ultrapower of the universe of sets by U . Can there be a nontrivial elementary embedding from V_U to itself? By [7, Theorem 3.3, Theorem 4.29], the answer is no if $V = \text{HOD}$ or if U is κ^+ -complete where κ is extendible. Nevertheless, we answer the question positively assuming the consistency of a measurable limit of measurable cardinals:

Theorem 1.2. *It is consistent with ZFC that for some normal ultrafilter U , there is an elementary embedding from V_U to itself.*

We then consider the question of ultrafilters with the same ultrapower. Suppose U and W are countably complete ultrafilters such that $V_U = V_W$. Must U and W be isomorphic (that is, Rudin–Keisler equivalent)? Woodin observed that the answer is no [7, Theorem 3.1], though again this is true if $V = \text{HOD}$. We consider the weaker question: must there exist $X \in U$ and $Y \in W$ with $|X| = |Y|$? Again, we show the answer is no after a discrete Magidor product of Prikry forcings, assuming the consistency of a limit of measurable cardinals of measurable cofinality:

Theorem 1.3. *It is consistent with ZFC that there are countably complete uniform ultrafilters U and W on distinct cardinals such that $V_U = V_W$.*

Recall that the Ultrapower Axiom (UA) [6] states that for any two countably complete ultrafilters U, W , there are $W' \in V_U$ and $U' \in V_W$ such that W' is a countably complete ultrafilter in V_U , U' is a countably complete ultrafilter in V_W , $(V_U)_{W'} = (V_W)_{U'}$ and $j_{W'} \circ j_U = j_{U'} \circ j_W$. The Weak Ultrapower Axiom (Weak UA) is the same statement, omitting the requirement that $j_{W'} \circ j_U = j_{U'} \circ j_W$.

The conclusions of the previous theorems are incompatible with UA by [7, Theorem 5.2]. Therefore UA typically becomes false after performing a discrete Magidor product of Prikry forcings. Nevertheless, starting from a model of UA containing no measurable cardinals δ of Mitchell order 2^{2^δ} ,

our main technical result (Theorem 5.7) yields a classification of the lifts of κ -complete ultrafilters on κ to the forcing extension.

This classification suffices to show in certain cases that Weak UA holds in the forcing extension. This answers a question of the second author [6, Question 9.2.4], assuming there is a measurable limit of measurable cardinals:

Theorem 1.4. *The Weak Ultrapower Axiom does not imply the Ultrapower Axiom.*

The above results follow from our main technical theorem which is an analysis of all possible extensions of κ -complete ultrafilters over κ whose ultrapower can be factored into a finite iterated ultrapower by normal ultrafilters. The following consequence gives a sense of what this classification entails:

Theorem 1.5. *Suppose that $W \in V$ is a κ -complete ultrafilter over κ that can be factored into a finite iteration of normal ultrafilters. Let G be V -generic for a discrete Magidor product of Prikry forcings. Then in $V[G]$, W extends to at most countably many countably complete ultrafilters.*

Moreover, if W^ is an extension of W , then $j_{W^*} \restriction V = i \circ e \circ j_W$, where $e : V_W \rightarrow N$ is a finite external iteration of V_W by normal measures and i is an internal iterated ultrapower of N by normal measures.*

The previous theorem also gives a sense in which our classification generalizes Kaplan's result.

This paper is organized as follows:

- In Section §2 we prove some preliminary results regarding ultrapowers and the discrete Magidor product.
- In Section §3 we study the complete iteration by a sequence of normal measures and how it relates to the restriction of an ultrapower of the generic extension to the ground model.
- In Section §4 we describe an ultrafilter which has many extensions to the generic extension of the discrete Magidor product and characterize its extensions. Also, we provide the example of a non-rigid ultrapower.
- In Section §5 we prove our characterization of lifts of ultrafilters to the generic extension by the discrete Magidor product.
- In Section §6 we prove some applications of our characterization: a model of weak UA which fails to satisfy UA, and an example of the same ultrapower by ultrafilters on different cardinals.
- In Section §7 we present some related open problems.

2. PRELIMINARIES

2.1. Derived ultrafilters and commuting squares. Let P be a transitive model of set theory and let U be a (possibly external) P -ultrafilter over

a set $X \in P$.¹ We will always assume that U is countably complete; namely, for any countable $\mathcal{A} \subseteq U$, $\bigcap \mathcal{A} \neq \emptyset$. Denote by $j_U^P : P \rightarrow P_U$ the ultrapower of P by U using functions $f : X \rightarrow P$ in P . We will suppress the superscript P from j_U^P whenever there is no ambiguity. Since U is countably complete, P_U is well-founded and we identify P_U with its transitive collapse.

Let $j : P \rightarrow Q$ be an elementary embedding of transitive models of set theory, $X \in P$, and $a \in j(X)$. The P -ultrafilter on X derived from j and a is the set

$$U = \{A \in P(X) \cap P \mid a \in j(A)\}$$

(The underlying set X is typically suppressed.) It is well known that U is a P -ultrafilter and that the map $k : P_U \rightarrow Q$ defined by $k([f]_U) = j(f)(a)$ is the unique elementary embedding mapping $[id]_U$ to a such that $k \circ j_U = j$. The following generalization of this fact will be used implicitly in many calculations below:

Lemma 2.1 (Shift lemma). *Suppose $i : P \rightarrow Q$ is an elementary embedding, W is a Q -ultrafilter over a set in $\text{rng}(i)$ and $U = i^{-1}[W]$. Then the embedding $k : P_U \rightarrow Q_W$ defined by $k([f]_U) = [i(f)]_W$ is well-defined and elementary. Moreover, it is the unique embedding mapping $[id]_U$ to $[id]_W$ such that the following diagram commutes:*

$$\begin{array}{ccc} Q & \xrightarrow{j_W} & Q_W \\ i \uparrow & & \uparrow k \\ P & \xrightarrow{j_U} & P_U \end{array}$$

Proof. Note that U is the P -ultrafilter derived from $j_W \circ i$ and $[id]_W$. Moreover, k is the associated factor map, and the lemma follows. \square

Suppose $i : M \rightarrow N$ is an elementary embedding and $X \subseteq N$. Then $\text{Hull}^N(i[M] \cup X)$ denotes $\{i(f)(s) : s \in X^{<\omega}, f \in M\}$. This is the smallest elementary substructure of N containing $i[M] \cup X$.

Lemma 2.2. *Suppose that D is a P -ultrafilter, $j : P \rightarrow M$, $j' : P_D \rightarrow M'$, and $k : M \rightarrow M'$ is such that $M' = \text{Hull}^{M'}(\text{rng}(k) \cup \text{rng}(j'))$ and the following diagram commutes:*

$$\begin{array}{ccc} P_D & \xrightarrow{j'} & M' \\ j_D \uparrow & & \uparrow k \\ P & \xrightarrow{j} & M \end{array}$$

Then if D' is the M -ultrafilter derived from k and $j'([id]_D)$, $M_{D'} = M'$, $k = j_{D'}$, and $[id]_{D'} = j'([id]_D)$.

¹That is, U is an ultrafilter on the Boolean algebra $P(X) \cap P$.

Proof. Note that there is a factor map $k' : M_{D'} \rightarrow M'$ defined by $k'([f]_{D'}) = k(f)(j'([id]_D))$ such that $k' \circ j_{D'} = k$. To see that k' is onto, we have

$$\begin{aligned} M' &= \text{Hull}^{M'}(\text{rng}(k) \cup \text{rng}(j')) \\ &= \text{Hull}^{M'}(\text{rng}(k) \cup \text{rng}(j' \circ j_D) \cup \{j'([id]_D)\}) \\ &= \text{Hull}^{M'}(\text{rng}(k) \cup \{j'([id]_D)\}) \subseteq \text{rng}(k') \end{aligned}$$

Since k' is an isomorphism of transitive models, k' is the identity. Also $[id]_{D'} = k'([id]_{D'}) = j'([id]_D)$, proving the lemma. \square

Corollary 2.3. *If $k : M \rightarrow M'$, $M' = \text{Hull}^{M'}(\text{rng}(k) \cup \{a\})$, and $a \in k(X)$ for some $X \in M$, then $M_D = M'$ and $k = j_D$ where D is the M -ultrafilter over X derived from a and k and $[id]_D = a$.*

Proof. This is a special case of the previous lemma where $j = id$ and j' is the factor embedding. \square

2.2. Iterations and products of Prikry-type forcings. We define the *Magidor support iteration* $\langle \mathbb{P}_\alpha, Q_\beta \mid \alpha \leq \kappa, \beta < \kappa \rangle$ associated with a sequence of names $\langle \mathcal{U}_\alpha \mid \alpha \in \Sigma \rangle$ where $\Sigma \subseteq \kappa$ is a set of measurable cardinals.

Definition 2.4 ([11, 4]). The forcing \mathbb{P}_α is defined inductively for each $\alpha \leq \kappa$: a condition p belongs to \mathbb{P}_α if it is a function p with $\text{dom}(p) = \alpha$ such that:

- (1) for every $\beta < \alpha$, $p \restriction \beta \in \mathbb{P}_\beta$.
- (2) for every $\beta < \alpha$, $p \restriction \beta \Vdash_{\mathbb{P}_\beta} p(\beta) \in Q_\beta$, where Q_β is trivial unless $\beta \in \Sigma$, in which case $\Vdash_{\mathbb{P}_\beta} \mathcal{U}_\beta$ is a normal ultrafilter over β and Q_β is a \mathbb{P}_β -name for the usual Prikry forcing² $Pr(\mathcal{U}_\beta)$ from [13].
- (3) there is a finite set b_p such that for every $\beta \in \alpha \setminus b_p$, $p \restriction \beta \Vdash_{\mathbb{P}_\beta} p(\beta) \leq^* 1_{Q_\beta}$.

We define $p \leq q$ iff for every $\beta < \alpha$, $p \restriction \beta \Vdash_{\mathbb{P}_\beta} p(\beta) \leq q(\beta)$. Also define $p \leq^* q$ iff for every $\beta < \alpha$, $p \restriction \beta \Vdash_{\mathbb{P}_\beta} p(\beta) \leq^* q(\beta)$.

Magidor [11, §2] originally defined his forcing so that for a condition $p \in \mathbb{P}_\alpha$, and $\beta \in \Sigma \cap \alpha$, $p(\beta) = (t, \mathcal{A})$, where t_β^p is a finite sequence of ordinals and \mathcal{A} is a \mathbb{P}_β -name such that $\Vdash_{\mathbb{P}_\beta} \mathcal{A} \in \mathcal{U}_\beta$. A straightforward inductive argument shows that this is a dense set of conditions in the forcing defined above.

A set of ordinals Δ is called *discrete* if it contains none of its accumulation points; that is, for every $\alpha \in \Delta$, $\sup(\Delta \cap \alpha) < \alpha$. In particular, Δ is an extremely thin non-stationary set, and so are all its restrictions to $\alpha < \sup(\Delta)$; similarly, if $\Delta \subseteq \kappa$ is discrete, then for every κ -complete ultrafilter U over κ , $\kappa \notin j_U(\Delta)$. Note that if κ is the least measurable limit of measurable cardinals, then the set of measurables below κ is discrete.

²Recall that $Pr(U)$ consists of pairs $(t, A) \in [\kappa]^{<\omega} \times U$, where $\max(t) < \min(A)$. It is equipped with two orders, $(t, A) \leq (s, B)$ iff $t \cap \max(s) = s$ and $A \subseteq B$, and $(t, A) \leq^* (s, B)$ iff $t = s$ and $A \subseteq B$. Thus $1_{Pr(U)} = (\emptyset, \kappa)$.

Notation 2.5. For the rest of this section, we fix a discrete set $\Delta \subseteq \kappa$ of measurable cardinals and a sequence $\vec{U} = \langle U_\alpha \mid \alpha \in \Delta \rangle$ such that U_α is a normal measure of Mitchell order 0 over α .

We will consider the Magidor iteration associated to $\langle \bar{U}_\beta \mid \beta \in \Delta \rangle$ where \bar{U}_β is a \mathbb{P}_β -name for the filter generated by U_β in $V^{\mathbb{P}_\beta}$ (see Proposition 2.7(2)).

Remark 2.6. Since the set Δ is discrete, a Magidor support here is always going to be non-stationary. Hence the forcing above inherits the properties of both the non-stationary and Magidor support iterations of Prikry-type forcings on the set Δ .

Proposition 2.7. (1) \mathbb{P}_κ is κ^+ -cc.

(2) If $\alpha \in \Delta$, U_α generates a normal ultrafilter in $V^{\mathbb{P}_\alpha}$.

Item (2) follows from Lévy-Solovay. For the proof of (1) see [11, 4.4].

Proposition 2.8. The set of conditions $p \in \mathbb{P}_\kappa$ such that for every $\beta \in \Delta$, $p(\beta) = \check{q}$ for some $q \in Pr(U_\beta)$ is \leq -dense in \mathbb{P}_κ .

Proof. Let $p \in \mathbb{P}_\kappa$ be a condition, and without loss of generality, assume that for each $\beta \in \Delta$, $p(\beta) = (t_\beta, \check{A}_\beta)$, where $t_\beta \in [\beta]^{<\omega}$. For $\beta \in \Delta$, define $p^*(\beta) = (t_\beta, A_\beta^*)$ by setting $A_\beta^* = \{\gamma < \beta \mid p \restriction \beta \Vdash_{\mathbb{P}_\beta} \check{\gamma} \in \check{A}_\beta\}$. A Lévy-Solovay-like argument shows that $p^* \in \mathbb{P}_\kappa$, and this is clearly a direct extension of p . \square

If $p \in \mathbb{P}_\alpha$ belongs to the dense set of the previous proposition, for $\beta \in \Delta \cap \alpha$, we denote by (t_β^p, A_β^p) the unique $q \in Pr(U_\beta)$ such that $p(\beta) = \check{q}$.

Definition 2.9. The *Magidor support product* $\prod_{\alpha \in \Delta} Pr(U_\alpha)$ consists of all functions p such that $\text{dom}(p) = \Delta$, $p(\alpha) \in Pr(U_\alpha)$, and $\{\alpha \in \Delta : p(\alpha) \leq^* 1\}$ is cofinite.

By the previous proposition, we obtain the following corollary:

Corollary 2.10 (Magidor). \mathbb{P}_κ is forcing equivalent to the Magidor support product $\prod_{\beta \in \Delta \cap \alpha} Pr(U_\beta)$.

We shall often treat \mathbb{P}_κ as if it were the product $\prod_{\beta \in \Delta} Pr(U_\beta)$.

As usual in iterated forcing, one can construct factor forcings $\mathbb{P}_{[\alpha, \beta)} \in V^{\mathbb{P}_\alpha}$ such that $\mathbb{P}_\alpha * \mathbb{P}_{[\alpha, \beta)} \cong \mathbb{P}_\beta$. This works in general for the Magidor iteration (and other iterations of Prikry-type forcings), but in the discrete case considered here, the factor forcing takes a simpler form: it is forcing equivalent to the Magidor product $\prod_{\xi \in \Delta \cap [\alpha, \beta)} Pr(U_\xi)$. (One can use compute this forcing in V or $V^{\mathbb{P}_\alpha}$; the former factor forcing is dense in the latter.) We also define $\mathbb{P}_{(\alpha, \beta)} = \prod_{\xi \in \Delta \cap (\alpha, \beta)} Pr(U_\xi)$, etc.

Lemma 2.11 (Prikry Lemma). For every $p \in \mathbb{P}_\kappa$, and every sentence σ in the forcing language for \mathbb{P}_κ , there is $p^* \leq^* p$ such that $p^* \Vdash \sigma$.

2.3. On ground model ultrafilters that generate ultrafilters in the extension. In this subsection, we provide a version of Theorem 1.1 which provides slightly more information in the context of discrete sequences of measures.

Definition 2.12. Suppose λ is a measurable cardinal and $\Sigma \subseteq \lambda$ is unbounded. A λ -complete ultrafilter U over λ is called Σ -mild if there is a function $f : \lambda \rightarrow \lambda$ such that

$$[id]_U \leq j_U(f)(\lambda) < \min(j_U(\Sigma) \setminus \lambda)$$

Note that if U is a normal measure with $\Sigma \notin U$, then U is Σ -mild. Also, every Σ -mild ultrafilter is a p -point.

Theorem 2.13. *If U is a $(\Delta \cap \lambda)$ -mild ultrafilter over a cardinal $\lambda \notin \Delta$, then U generates a λ -complete ultrafilter in $V^{\mathbb{P}_\kappa}$.*

Proof. Let $G \subseteq \mathbb{P}_\lambda$ be V -generic. Note that it suffices to show that U generates an ultrafilter in $V[G]$, because the factor forcing $\mathbb{P}_{[\lambda, \kappa]}$ does not add subsets to λ since $\lambda \notin \Delta$.

By Gitik and Kaplan [5, Prop. 2.6 and Prop. 2.7], since λ and λ^+ remain regular in $V[G]$, it suffices to prove that $j_U[G]$ decides all statements of the form $[id]_U \in j_U(\dot{A})$, where \dot{A} is a \mathbb{P}_κ -name for a subset of λ . Given such a name \dot{A} , we may assume that it is a $\mathbb{P}_\kappa \restriction \lambda$ -name.

Let us work in $V_U[G]$. Let \dot{A}_0 be the $\mathbb{P}_{(\lambda, j_U(\lambda))}$ -name obtained from $j_U(\dot{A})$. By the Prikry property, there is a condition $q \leq^* 1_{\mathbb{P}_{(\lambda, j_U(\lambda))}}$ such that $q \parallel "[id]_U \in \dot{A}_0"$ and therefore there is $p \in G$ such that

$$p \Vdash q \parallel "[id]_U \in j_U(\dot{A})."$$

In other words, $(p, q) \parallel "[id]_U \in j_U(\dot{A})"$. Let us show that there is $p' \in G$ such that $j_U(p') \leq (p, q)$. Fix a sequence $\langle A_\gamma : \gamma \in j_U(\Delta) \cap (\lambda, j_U(\lambda)) \rangle \in V_U$ such that for all $\gamma \in \text{dom}(q)$, $q(\gamma) = (\emptyset, A_\gamma)$. Let

$$\alpha \mapsto \langle A_\gamma^{(\alpha)} \mid \gamma \in \Delta \cap [\pi(\alpha), \lambda) \rangle$$

represent q in j_U where π is the function representing λ in V_U .

Let us proceed with a density argument. Let $p \in \mathbb{P}_\kappa$. We shrink p in the interval $[\gamma_0, \lambda)$, where $\gamma_0 = \max(b_p \cap \lambda) + 1$. For $\gamma \geq \gamma_0$, $\gamma \in \Delta \cap \lambda$, define $A_\gamma^0 = \Delta_{\delta < \gamma} A_\gamma^{(\delta)}$. Moreover, given that f witnesses that U is $(\Delta \cap \lambda)$ -mild, if $f(\sup(\Delta \cap \gamma)) \geq \gamma$ we let $A_\gamma^* = A_\gamma^0 \setminus \sup(\Delta \cap \gamma)$ and if $f(\sup(\Delta \cap \gamma)) < \gamma$ we let

$$A_\gamma^* = A_\gamma^0 \setminus \max\{f(\sup(\Delta \cap \gamma)), \sup(\Delta \cap \gamma)\}.$$

We shrink p so that $A_\gamma^p \subseteq A_\gamma^*$ for $\gamma \in \Delta \setminus \gamma_0$, and by genericity we can find such a $p^* \in G$ such that $p^* \leq p$. Then $j_U(p^*) \restriction \lambda = p^* \leq p$ and $j_U(p^* \restriction [\lambda, \kappa)) \leq j_U(p \restriction [\lambda, \kappa))$. For $\gamma \in j_U(\Delta) \cap [\lambda, j_U(\kappa))$, we note that $\lambda \notin j_U(\Delta)$ by our assumption that $\lambda \notin \Delta$ and Δ is discrete. We need to

argue that $A_\gamma^{j_U(p^*)} \subseteq A_\gamma$. Denote by

$$j_U(\alpha \mapsto \langle A_\gamma^{(\alpha)} \mid \gamma \in \Delta \cap [\pi(\alpha), \lambda) \rangle)(\beta) = \langle A_{\beta, \gamma} \mid \gamma \in j_U(\Delta) \cap [j_U(\pi)(\beta), j_U(\lambda)) \rangle.$$

Then by definition, $A_{[id]_U, \gamma} = A_\gamma$ for every $\gamma \in j_U(\Delta) \cap [\lambda, j_U(\lambda))$. If $\gamma = \min(j_U(\Delta) \setminus \lambda)$, then $j_U(f)(\sup(j_U(\Delta) \cap \lambda)) = j_U(f)(\lambda) \geq [id]_U$ and we have

$$A_\gamma^{j_U(p^*)} \subseteq \Delta_{\beta < \gamma} A_{\beta, \gamma} \setminus j_U(f)(\lambda) + 1 \subseteq A_{[id]_U, \gamma} = A_\gamma.$$

If $\gamma > \min(j_U(\Delta) \setminus \lambda)$, then $\sup(j_U(\Delta) \cap \gamma) \geq \min(j_U(\Delta) \cap \gamma) \geq [id]_U$, hence we still have $A_\gamma^{j_U(p^*)} \subseteq A_\gamma$. It follows that $j_U(p^*) \leq p \wedge q$ as wanted. \square

The discreteness of the set Δ is essential here; without it, even 0-order normal measures might not generate ultrafilters. We give an example of this behavior due to Ben-Neria in Example 3.9.

Example 2.14. In Section 4.1, we will give an example where U does not generate an ultrafilter in $V[G]$ even though $[id]_U < \min(j_U(\Delta) \setminus \kappa)$. Hence the assumption regarding the existence of the function f cannot be removed in Theorem 2.13.

Note that if $[id]_U$ is below the first M_U -Ramsey cardinal (for example) above λ , then U is Δ -mild. Moreover, by the counterexample of Section 4.1, $[id]_U$ being below the first M_U -measurable cardinal does not suffice for U to be Δ -mild, or even for U to generate an ultrafilter in $V[G]$.

3. THE COMPLETE ITERATION

One aspect of understanding the lifts \overline{W} of an ultrafilter W to a generic extension $V[G]$ is to analyze the factor map $k : V_W \rightarrow j_{\overline{W}}^{V[G]}(V)$ defined by $k([f]_W) = [f]_{W^*}^{V[G]}$. In the case of a generic extension by an iteration of Prikry forcings, the factor map can often be described in terms of the complete iteration:

Definition 3.1. Let $\vec{U} = \langle U_\delta \mid \delta \in \Delta \rangle$ be a sequence such that U_δ is a normal measure on δ and Δ is any set of measurables. Let us define, by transfinite recursion, the *complete iteration* associated with the sequence \vec{U} . This will be an iterated ultrapower of V denoted by

$$\langle N_\alpha, i_{\alpha, \beta}^{(\vec{U})} \mid \alpha \leq \beta \leq \theta \rangle$$

starting with $N_0 = V$. Simultaneously, we will define sets of ordinals $\langle s_\delta^\alpha \mid \delta \in i_{0, \alpha}(\Delta) \rangle$ starting with $s_\delta^0 = \emptyset$ for all $\delta \in \Delta$.

For $\alpha < \theta$, let $W_\alpha = i_\alpha(\vec{U})_{\delta_\alpha}$ where $\delta_\alpha \in i_\alpha(\Delta)$ is the minimal δ such that the set s_δ^α is finite. Let $N_{\alpha+1} = (N_\alpha)_{W_\alpha}$, and let $i_{\alpha, \alpha+1} : N_\alpha \rightarrow N_{\alpha+1}$ be the ultrapower embedding associated with W_α . Define

$$s_\beta^{\alpha+1} = \begin{cases} \emptyset & \beta \in i_{\alpha+1}(\Delta) \setminus i_{\alpha, \alpha+1}[\Delta] \\ s_{\delta_\alpha}^\alpha \cup \{\delta_\alpha\} & \beta = i_{\alpha, \alpha+1}(\delta_\alpha) \\ s_\beta^\alpha & o.w. \end{cases}.$$

At limit steps ρ , we take the direct limits of the embeddings and let $s_\beta^\rho = \bigcup \{s_{\beta'}^\alpha \mid \alpha < \rho, i_{\alpha,\rho}(\beta') = \beta\}$ for every $\beta \in i_\rho(\Delta)$. The sequence $\langle s_\alpha^\theta \mid \alpha \in i_{0,\theta}(\Delta) \rangle$ is called the *sequence of sets of indiscernibles* associated with the complete iteration of \vec{U} .

We usually omit the superscript \vec{U} from $i^{\vec{U}}$, and we denote θ by ∞ when the length of the iteration does not play a significant role.

For example, if Δ consists of a single measurable cardinal, then the complete iteration is simply the ω^{th} iterated ultrapower of the only normal measure in \vec{U} , and the sequence of sets of indiscernibles consists of the corresponding sequence of iteration points.

Proposition 3.2. *Let $i : V \rightarrow N$ be the complete iteration of \vec{U} , where $\text{dom}(\vec{U}) = \Delta$ is discrete. Then:*

- (1) *For every α , $\delta_{\alpha+1} = i_{\alpha,\alpha+1}(\delta_\alpha)$.*
- (2) *For each $\gamma \in \Delta$, there is a unique $\alpha = \alpha(\gamma)$ such that $\delta_\alpha = \gamma$.*
- (3) *For each $\gamma \in \Delta$, $i_{0,\alpha}(\gamma) = \gamma$, and $i(\gamma) = i_{\alpha,\alpha+\omega}(\gamma)$, where $\alpha = \alpha(\gamma)$.*

Proof. For (1), we have that $i_\alpha(\Delta) \cap \delta_\alpha$ is bounded in δ_α , and therefore

$$i_{\alpha+1}(\Delta) \cap i_{\alpha,\alpha+1}(\delta_\alpha) = i_\alpha(\Delta) \cap \delta_\alpha.$$

Hence every $\delta \in i_{\alpha+1}(\Delta) \cap i_{\alpha,\alpha+1}(\delta_\alpha)$ has been used infinitely many times and $\delta_{\alpha+1} \geq i_{\alpha,\alpha+1}(\delta_\alpha)$. By definition of δ_α , equality must hold.

For (2) and (3), fix any $\gamma \in \Delta$, then γ is measurable, it is routine to show inductively on β , if $\delta_\beta < \gamma$, then $i_{0,\beta}(\gamma) = \gamma$. Since the sequence δ_α is strictly increasing, and since Δ is discrete, after less than γ -many steps of the iteration we reach a stage α , such that $\gamma = \delta_\alpha$. This means that the measure $i_{0,\alpha}(\vec{U})_\gamma$ was not used before stage α , and every previous measure was used infinitely many times already. By (1), $\delta_{\alpha+n} = i_{\alpha,\alpha+n}(\gamma)$, for every $n < \omega$. At stage $\alpha + \omega$ we get:

$$i_{\alpha,\alpha+\omega}(i_{0,\alpha}(\Delta)) = [i_{0,\alpha}(\Delta) \cap \gamma] \cup i_{\alpha,\alpha+\omega}(i_{0,\alpha}(\Delta) \setminus \gamma)$$

So the minimal element which can potentially be applied now is $i_{\alpha,\alpha+\omega}(\gamma)$, however, we have already used this measurable ω -many times, so by the definition of the complete iteration we must go to the next element which makes the critical point of $i_{\alpha+\omega,\theta}$ greater than $i_{\alpha,\alpha+\omega}(\gamma)$. We conclude that $i_{\alpha+\omega,\theta}(i_{\alpha,\alpha+\omega}(\gamma)) = i_{\alpha,\alpha+\omega}(\gamma)$ and therefore $i(\gamma) = i_{\alpha,\alpha+\omega}(\gamma)$ as wanted. Also we see that for every α ,

$$i(\Delta) = i_{0,\alpha}(\Delta) \cap \delta_\alpha \cup \{i_{\alpha,\alpha+\omega}(\delta_\alpha)\} \cup i(\Delta) \setminus i_{\alpha,\alpha+\omega}(\delta_\alpha)$$

□

Definition 3.3. Given a sequence of sets of ordinals $\vec{s} = \langle s_\alpha \mid \alpha \in \Delta \rangle$, each of order type ω , we associate a filter $G_{\vec{s}}$ on \mathbb{P}_κ consisting of all conditions p such that for each α , t_α^p is an initial segment of s_α and $s_\alpha \setminus t_\alpha^p \subseteq A_\alpha^p$.

Suppose $i : M \rightarrow N$ is elementary, $\mathbb{P} \in M$ is a poset, and $G \subseteq i(\mathbb{P})$ is N -generic. Then

$$\text{Hull}^{N[G]}(i[M] \cup \{G\}) = \{i(\tau)_G : \tau \in M^{\mathbb{P}}\}.$$

Then $\text{Hull}^N(i[M] \cup \{G\})$ is the smallest elementary substructure of $N[G]$ containing $i[M] \cup \{G\}$. That it is an elementary substructure can be proved by verifying the Tarski-Vaught criterion using the Fullness Lemma in forcing; see [8, Corollary 25] for a different approach using Boolean ultrapowers.

Lemma 3.4. *Let \vec{U} be a sequence of normal measures on a discrete set Δ with $\sup(\Delta) = \kappa$. Let $i = i_{0,\theta} : V \rightarrow N$ be the complete iteration of V by \vec{U} , and $\vec{s} = \langle s_\alpha^\theta \mid \alpha \in i(\Delta) \rangle$ be the sequence of sets of indiscernibles, and let $G = G_{\vec{s}}$. Then the following hold:*

- (1) G is N -generic for $i(\mathbb{P}_\kappa)$.
- (2) If p is a pure condition then $i(p) \in G$.
- (3) $N[G] = \text{Hull}^{N[G]}(i[V] \cup \{G\})$.
- (4) $N[G]$ is closed under δ -sequences where $\delta = \min(\Delta)$.

Proof. The genericity of G is due to Fuchs [3]. For the second item, if p is pure, then by induction we can prove that for every $\xi \leq \theta$, $s_\alpha^\xi \subseteq A_\alpha^{i_0,\alpha(p)}$. This implies in particular that $s_\alpha^\theta \subseteq A_\alpha^{i(p)}$, as wanted. Suppose this was true for ξ , since $i_{\xi,\xi+1}$ is the ultrapower by the normal W_ξ on δ_ξ , and $A^{i_0,\xi(p)} \in W_\xi$, we conclude that $\delta_\xi \in A_{\delta_\xi}^{i_{\xi,\xi+1}(p)}$. Since below δ_ξ , things do not change, we get that $s_{i_{\xi,\xi+1}(\delta_\xi)}^{\xi+1} \subseteq A_{\delta_\xi}^{i_{\xi,\xi+1}(p)}$. Note that above ξ , all the sequences are empty at this stage of the iteration.

For the third item, let $H = \text{Hull}^{N[G]}(i[V] \cup \{G\})$. To establish that $H = N[G]$, we will show that $N \subseteq H$. Then $H = N[G]$ since $H \prec N[G]$ and $N \cup \{G\} \in H$.

Let $S = \bigcup \vec{s}$, the set of critical points of the complete iteration. Then S is itself discrete and the set of accumulation points $\text{acc}(S)$ equals $\text{acc}(i(\Delta))$. Since every element of N is of the form $i(f)(\kappa_1, \dots, \kappa_m)$ for some $f : [\kappa]^m \rightarrow V$, where $\kappa_1, \dots, \kappa_m \in S$, it suffices to prove that $S \subseteq H$. In turn, it suffices to prove that $i(\Delta) \subseteq H$, since any element in S is a Prikry point associated with one of the elements of $i(\Delta)$ and therefore is definable from G and $i(\Delta)$ in $N[G]$.

Suppose towards contradiction that ζ is the minimal element of $i(\Delta)$ not in H . Since $i(\Delta)$ is discrete, $\gamma = \sup(i(\Delta) \cap \zeta) < \zeta$. Note that $\gamma \notin H$, since otherwise easily $\zeta \in H$. It follows that $\gamma \in \text{acc}(i(\Delta))$ since otherwise $\gamma \in i(\Delta)$, and hence $\gamma \in H$ by the minimality of ζ . Note that $\gamma \subseteq H$. Note that $\gamma \notin S$ since S is discrete and $\gamma \in \text{acc}(i(\Delta)) \subseteq \text{acc}(S)$. Therefore $\gamma = i(f)(\kappa_1, \dots, \kappa_m)$ for some $\kappa_1, \dots, \kappa_m < \gamma$ and so $\gamma \in H$, which is a contradiction.

The final item follows from the previous one using the standard proof that the ultrapower of V by a δ -complete ultrafilter is closed under δ -sequences.

(In fact, one can view $N[G]$ as a Boolean ultrapower of V and apply [8, Theorem 28].) Fix a δ -sequence of elements $\langle x_\alpha \mid \alpha < \delta \rangle \subseteq N[G]$. By the previous item, each x_α is the interpretation of some $i(\tau_\alpha)$ via G . Note that

$$\langle i(\tau_\alpha) \mid \alpha < \delta \rangle = i(\langle \tau_\alpha \mid \alpha < \delta \rangle) \upharpoonright \delta \in N.$$

Therefore $\langle x_\alpha \mid \alpha < \delta \rangle \in N[G]$. \square

The following proposition shows that any ultrafilter used in the complete iteration gives rise to an elementary embedding of the target model of the complete iteration.

Proposition 3.5. *If $i = i_{0,\theta} : V \rightarrow N$ is the complete iteration V by \vec{U} , \vec{s} is the associated sequence of sets of indiscernibles, and U is an ultrafilter on δ applied at some stage of the complete iteration, then $j_U^{N[G_{\vec{s}}]} \circ i = i$ and $j_U^{N[G_{\vec{s}}]}(\vec{s}) = \vec{s} \setminus \{\delta\}$.*

Proof. We first consider the special case that δ is the least element of the domain of \vec{U} . Note that $j_U^{N[G_{\vec{s}}]} = j_U^V \upharpoonright N[G_{\vec{s}}]$ because $N[G_{\vec{s}}]$ is closed under δ -sequences. Therefore

$$j_U^{N[G_{\vec{s}}]} \circ i = j_U \circ i = j_U(i) \circ j_U = i^U \circ j_U$$

where $i^U : V_U \rightarrow N$ denotes the complete iteration of V_U by $j_U(\vec{U})$. By the definition of the complete iteration, $i^U \circ j_U = i$, which proves that $j_U^{N[G_{\vec{s}}]} \circ i = i$. Similarly, $j_U^{N[G_{\vec{s}}]}(\vec{s})$ is the sequence of sets of indiscernibles associated with the complete iteration of V_U by $j_U(\vec{U})$, which is $\vec{s} \setminus \{\delta\}$.

To prove the claim in general, suppose U is the ultrafilter used at stage α of the complete iteration. Then $i = i_{\alpha\infty} \circ i_{0\alpha}$ where $i_{0\alpha} : V \rightarrow N_\alpha$ is an initial segment of the complete iteration V by \vec{U} and $i_{\alpha\infty} : N_\alpha \rightarrow N$ is the complete iteration of N_α by $\vec{W} = i_{0\alpha}(\vec{U}) \upharpoonright [\delta, \infty)$. Let $\vec{s}^{0\alpha}$ denote the sequence of sets of indiscernibles associated with $i_{0\alpha}$ and let $\vec{s}^{\alpha\infty}$ denote the sequence of sets of indiscernibles associated with $i_{\alpha\infty}$. Then $G_{\vec{s}^{0\alpha}} \times G_{\vec{s}^{\alpha\infty}} = G_{\vec{s}}$.

The special case of the claim proved above, applied in N_α to U and \vec{W} , implies that $j_U^{N[G_{\vec{s}^{\alpha\infty}}]} \circ i_{\alpha\infty} = i_{\alpha\infty}$ and $j_U^{N[G_{\vec{s}^{\alpha\infty}}]}(\vec{s}^{\alpha\infty}) = \vec{s}^{\alpha\infty} \setminus \{\delta\}$. This yields the full claim almost immediately, except that we have to verify that $j_U^{N[G_{\vec{s}^{\alpha\infty}}]}$ is the restriction of $j_U^{N[G_{\vec{s}}]}$ to $N[G_{\vec{s}^{\alpha\infty}}]$. But $j_U^{N[G_{\vec{s}}]} = j_U^{N[G_{\vec{s}^{0\alpha}} \times G_{\vec{s}^{\alpha\infty}}]}$, which extends $j_U^{N[G_{\vec{s}^{\alpha\infty}}]}$ by the proof of the classical Lévy-Solovay theorem [10]. \square

3.1. The canonical extension of an ultrafilter. Suppose that in V , W is a κ -complete ultrafilter on a set X . Using a construction due to Mitchell [12], we will define a κ -complete $V[G]$ -ultrafilter $W^* \in V[G]$ extending W . (The extension W^* is essentially due to Magidor; it is the construction of W^* using complete iterations that is due to Mitchell.)

Let $j : V \rightarrow M$ be the ultrapower embedding associated with W . Let $\mathbb{Q} = \mathbb{P}_{>\kappa}$, so that $j(\mathbb{P}_\kappa)$ can be naturally identified with $\mathbb{P}_\kappa \times \mathbb{Q}$. To lift j

to $V[G]$, one might try to produce an M -generic H on \mathbb{Q} such that $j[G] \subseteq G \times H$. If Δ is unbounded in κ , however, no such M -generic H can exist in $V[G]$: the ordinal $\delta = \min(j(\Delta) \cap (\kappa, j(\kappa)))$ has uncountable cofinality in $V[G]$, so in $V[G]$, there is no cofinal ω -sequence in δ .

Instead, we will produce an inner model N and an elementary embedding $i : M \rightarrow N$ such that there is an N -generic filter H on $i(\mathbb{Q})$ with $i \circ j[G] \subseteq G \times H$. Then by the Silver lifting criterion, $i \circ j$ lifts to an elementary embedding from $V[G]$ to $N[G \times H]$.

Let $i : M \rightarrow N$ be the complete iteration of M via the sequence $j(\vec{U}) \restriction (\kappa, j(\kappa))$. Let \vec{s} be the sequence of sets of indiscernibles associated with the complete iteration, and let $G_{\vec{s}}$ be the associated N -generic filter on $i(\mathbb{Q})$ (Definition 3.3).

Note that G is an $N[G_{\vec{s}}]$ -generic filter on \mathbb{P}_κ , and so by the Product Lemma, $G \times G_{\vec{s}}$ is an N -generic filter on $\mathbb{P}_\kappa \times \mathbb{Q}$. We must verify that $i \circ j[G] \subseteq G \times G_{\vec{s}}$. For each $p \in \mathbb{P}_\kappa$, $j(p)$ has the form (p, q) where $q \in \mathbb{Q}$ is a *pure condition*, or in other words, a direct extension of $1_{\mathbb{Q}}$, and therefore $i \circ j(p) = (p, i(q))$. For every pure condition $q \in \mathbb{Q}$, $i(q)$ belongs to H , by Lemma 3.4. Hence $i \circ j(p) = (p, i(q)) \in G \times G_{\vec{s}}$.

By the Silver lifting criterion, let $j^* : V[G] \rightarrow N[G \times G_{\vec{s}}]$ be the unique lift of $i \circ j$ such that $j^*(G) = G \times G_{\vec{s}}$.

Definition 3.6. The *canonical extension* of W to $V[G]$ is the $V[G]$ -ultrafilter W^* on X derived from j^* using $i([\text{id}]_W)$.

Note that W^* is κ -complete in $V[G]$ since it is derived from j^* , which has critical point at least κ .

The next proposition shows $N[G \times G_{\vec{s}}] = V[G]_{W^*}$ and $j^* = j_{W^*}$.

Proposition 3.7. *Suppose W is a κ -complete ultrafilter and W^* is the canonical extension of W to $V[G]$. Then $j_{W^*} \restriction V = i \circ j_W$ where $i : V_W \rightarrow N$ is the complete iteration of V_W associated with $j_W(\vec{U}) \restriction (\kappa, j_W(\kappa))$. Moreover, $j_{W^*}(G) = G \times G_{\vec{s}}$ where \vec{s} is the sequence of sets of indiscernibles associated with the complete iteration.*

Proof. The proposition follows from Corollary 2.3 once we show that

$$N[G \times G_{\vec{s}}] = \text{Hull}^{N[G \times G_{\vec{s}}]}(i \circ j_W[V] \cup \{G, G_{\vec{s}}, i([\text{id}]_W)\}).$$

This in fact implies directly that $j_{W^*} = j^*$. To see the above, applying the third item of Lemma 3.4 inside of M , we see that

$$N[G_{\vec{s}}] = \text{Hull}^{N[G_{\vec{s}}]}(i \circ j_W[V] \cup \{G_{\vec{s}}, i([\text{id}]_W)\}).$$

Then we finish by noting that being a forcing extension of $N[G_{\vec{s}}]$, $N[G \times G_{\vec{s}}]$ is the hull (in itself) of $N[G_{\vec{s}}] \cup \{G\}$. \square

In the case that W is Δ -mild, Theorem 2.13 shows that W^* is the unique extension of W in $V[G]$ and therefore Proposition 3.7 can be used to analyze the ultrapower of the ultrafilter generated by W in the generic extension. This is a slight generalization of Kaplan's theorem stated in the introduction.

Although this is just the combination of Theorem 2.13 and Proposition 3.7, we record it for future use.

Corollary 3.8. *Let W be a Δ -mild ultrafilter in V and let $G \subseteq \mathbb{P}_\kappa$ be V -generic. In $V[G]$, W generates its own canonical extension W^* and $j_{W^*} \restriction V = i \circ j_W$, where $i : V_W \rightarrow N$ is the complete iteration of M associated with $j(\vec{U}) \restriction (\kappa, j(\kappa))$. Moreover, $j_{W^*}(G) = G \times G_{\vec{s}}$ where \vec{s} is the sequence of sets of indiscernibles associated with the complete iteration.*

We now give Ben-Neria's counterexample to normal measures generating ultrafilters after (non-discrete) Magidor iterations.

Example 3.9. Suppose κ is a measurable cardinal of Mitchell order 2, Δ is the set of all measurable cardinals less than κ , and $G \subseteq \mathbb{P}_\kappa$ is V -generic for the Magidor iteration.

Take any normal measure U_1 over κ of Mitchell order 1 in the ground model. Ben-Neria [1, Notation 2.3] defines an ultrafilter U_1^\times as the projection of U_1^* by the function $d : \Delta \rightarrow \kappa$ mapping each measurable cardinal in Δ to the least element of its corresponding Prikry sequence.

By Ben-Neria [1, Proposition 2.1], U_1^\times is a normal measure in $V[G]$. Let $U_0 = U_1^\times \cap V$, so that U_0 is a normal ultrafilter in V by [5]. Also U_0 must be of order 0 (and in particular $U_0 \neq U_1$): otherwise, d would be a finite-to-one regressive function defined U_1^\times -large set.

Consider the ultrafilter U_0^* . Then U_0^* is a normal ultrafilter [1, 2.1] in $V[G]$ and we claim that $U_0^* \neq U_1^\times$, which yields two distinct extensions of U_0 to normal ultrafilters in $V[G]$. Indeed, since U_1 is of order 1, the set Δ of measurables below κ is in U_1 , and therefore, by definition $d[\Delta] \in d_*(U_1) = U_1^\times$. On the other hand, as U_0 is of order 0, $d[\Delta] \notin U_0^*$: otherwise, κ must appear in the Prikry sequence in $V[G]_{U_0^*}$ associated to some element of $j_{U_0^*}(\Delta)$, but by Proposition 3.7, the elements of these Prikry sequences are critical points in the complete iteration of V_{U_0} ; κ cannot be such a critical point since κ is not measurable in V_{U_0} . Hence $U_1^\times \neq U_0^*$.

3.2. Mitchell's lemma. Next, we prove a variation of Mitchell's lemma from [12], which gives an analysis of ultrapowers of canonical lifts within complete iterates of V that is a key part of the proof of our classification results in Section 5.2. The idea is to take a sufficiently complete ultrafilter W and a complete iteration $i : V \rightarrow N$ and analyze the ultrapower embedding associated to the canonical extension of $i(W)$ to $N[G_{\vec{s}}]$, where \vec{s} is the sequence of sets of indiscernibles. It turns out that this embedding is simply the restriction to $N[G_{\vec{s}}]$ of the ultrapower embedding $j_W : V \rightarrow V_W$.

Let \vec{U} be a sequence of normal measures on a discrete set $\Delta \subseteq \kappa$. Let $i = i_{0,\infty} : V \rightarrow N$ be the complete iteration of V by \vec{U} , and $\vec{s} = \langle s_\alpha^\infty \mid \alpha \in i(\Delta) \rangle$ be the associated sequence of sets of indiscernibles, and let $G = G_{\vec{s}}$.

Lemma 3.10 (Mitchell). *Suppose that W is a κ -complete ultrafilter. Then*

$$j_{i(W)^*}^{N[G_{\vec{s}}]} = j_W \restriction N[G_{\vec{s}}].$$

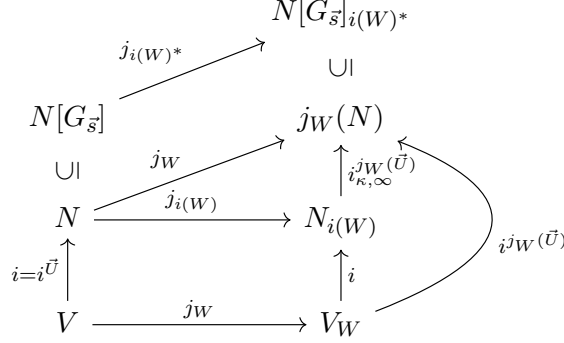


FIGURE 1. Mitchell's diagram

Moreover, the canonical factor map $k : N_{i(W)} \rightarrow j_{i(W)*}(N)$ is given by the complete iteration of $N_{i(W)}$ by $i(j_W(\vec{U})) \restriction (\kappa, j_W(\kappa))$.

Proof. By replacing κ with the completeness of W , we may assume that κ is a measurable cardinal, and in particular that κ is strongly inaccessible.

We first note the bottom rectangle in Figure 1 commutes; this is just by the usual formula $j_{i(W)} \circ i = i \circ j_W$.

Second, we note that for the same reason the quadrangle with vertices V , N , $j_W(N)$, and V_W also commutes, using here that $j_W(\vec{U}) \restriction \kappa = \vec{U}$ and therefore

$$j_W(i) = i^{j_W(\vec{U})} = i_{\kappa, \infty}^{j_W(\vec{U})} \circ i$$

For ease of notation, for any $j : V \rightarrow M$ obtained by composing arrows in the diagram, let $\vec{U}^M = j(\vec{U})$. (The fact that this is well-defined follows from the commutativity we have established.)

The commutativity established in the previous paragraphs allows us to show that

$$j_W \restriction N = j_{i(W)*}^{N[G_s]} \restriction N$$

To prove this, we first observe $i^{\vec{U}^{N_{i(W)}} \restriction (\kappa, \infty)} = i_{\kappa, \infty}^{\vec{U}^{V_W}}$, by the definition of the complete iteration: since $i_{0\kappa}^{\vec{U}^{V_W}} = i \restriction V_W$, which embeds V_W into $N_{i(W)}$, $i_{\kappa, \infty}^{\vec{U}^{V_W}}$ is the complete iteration of $\vec{U}^{N_{i(W)}}$ restricted to measures above κ .

Then by Proposition 3.7,

$$j_{i(W)*}^{N[G_s]} \restriction N = i^{\vec{U}^{N_{i(W)}} \restriction (\kappa, \infty)} \circ j_{i(W)} = i_{\kappa, \infty}^{\vec{U}^{V_W}} \circ j_{i(W)}$$

By the commutativity facts established in the first two paragraphs, $j_W \restriction N$ and $i_{\kappa, \infty}^{\vec{U}^{V_W}} \circ j_{i(W)}^N$ agree on $i[V]$. Moreover $j_W \restriction N$ and $i_{\kappa, \infty}^{\vec{U}^{V_W}} \circ j_{i(W)}^N$ agree on κ , both being the identity there. Since $N = \text{Hull}^N(i[V] \cup \kappa)$, it follows that $j_W \restriction N = j_{i(W)*}^{N[G_s]} \restriction N$ as claimed.

Next, to show that $j_{i(W)^*}^{N[G_{\vec{s}}]} = j_W \upharpoonright N[G_{\vec{s}}]$, it now suffices to prove that these two embeddings agree on $G_{\vec{s}}$. By elementarity, $j_W(G_{\vec{s}})$ is equal to the generic associated to the sequence $j_W(\vec{s})$ of sets of indiscernibles coming from the complete iteration of V_W by $j_W(\vec{U})$. But $j_{i(W)^*}(G_{\vec{s}})$ is equal to the same thing, by the “moreover” clause of Proposition 3.7 and calculations similar to the previous paragraph. \square

Corollary 3.11. *Suppose $\lambda \notin \Delta$ is a measurable cardinal and W is a λ -complete ultrafilter on λ . Then $j_{i(W)^*}^{N[G_{\vec{s}}]} = j_W \upharpoonright N[G_{\vec{s}}]$.*

Proof. By the previous lemma, it suffices to consider the case that $\lambda < \sup \Delta$. Also, the previous lemma implies that $j_{\bar{i}(W)^*}^{\bar{N}[G_{\vec{t}}]} = j_W \upharpoonright \bar{N}[G_{\vec{t}}]$ where $\bar{i} : V \rightarrow \bar{N}$ is the complete iteration of \vec{U} restricted to measures below λ and \vec{t} is the associated sequence of sets of indiscernibles.

Note however that $\bar{i}(W) = i(W)$, and by Lemma 3.4 applied in $\bar{N}[G_{\vec{t}}]$, $N[G_{\vec{s}}]$ is an inner model of $\bar{N}[G_{\vec{t}}]$ that is closed under λ -sequences in $\bar{N}[G_{\vec{t}}]$. It follows that

$$j_{i(W)^*}^{N[G_{\vec{s}}]} = j_{\bar{i}(W)^*}^{\bar{N}[G_{\vec{t}}]} \upharpoonright N[G_{\vec{s}}] = j_W \upharpoonright N[G_{\vec{s}}],$$

which proves the corollary. \square

3.3. Normal measures and the complete iteration. In our classification of lifts of ultrafilters under the discrete Magidor product we will have to classify the possible extensions of the point-wise images of a normal ultrafilter under the complete iteration. The next lemmas will be used for that purpose. The tail filter on an ultrafilter ρ is the filter generated by the sets $\{(\alpha, \rho) \mid \alpha < \rho\}$.

Lemma 3.12. *If $i : M \rightarrow N$ is an elementary embedding, $U \in M$ is a normal ultrafilter on δ , and $N = \text{Hull}^N(i[M] \cup i(\delta))$, then $F \cup i[U]$ generates $i(U)$ where F denotes the tail filter on $i(\delta)$.*

Proof. Let $X \in i(U)$. Since $N = \text{Hull}^N(i[M] \cup i(\delta))$, there is $f \in M$ and $\eta < i(\delta)$ such that $X = i(f)(\eta)$. Changing f if needed, we may assume that $f : \delta \rightarrow U$. Let $A^* = \Delta_{\alpha < \delta} f(\alpha)$, then by the normality assumption $A^* \in U$. It follows that $i(A^*) \setminus \eta + 1 \subseteq i(f)(\eta) = X$, and therefore X is in the filter generated by $F \cup i[U]$. \square

Lemma 3.13. *Suppose $i : M \rightarrow N$ is the complete iteration of \vec{U} , $\delta = \min(\text{dom}(\vec{U}))$, and $\eta \leq i(\delta)$. Let $X = \text{Hull}^N(i[M] \cup \eta)$, let $k : \bar{N} \rightarrow N$ be the inverse of the transitive collapse of X , and let $\bar{i} = k^{-1} \circ i$. Let $n \leq \omega$ be least such that $\eta \leq i_{0,n}(\delta)$. Then $\bar{i} = i_{0,n}$ and $k = i_{n,\infty}$.*

Proof. Let M_n be the (transitive) n^{th} -iterate of M in i , namely $i_{n,\infty} : M_n \rightarrow N$, and $i_{0,n} : M \rightarrow M_n$. We claim that $X = i_{n,\infty}[M_n]$, from which it follows via uniqueness that $i_{n,\infty} = k$ and therefore $\bar{i} = k^{-1} \circ i = i_{0,n}$. Indeed, any $x \in X$ has the form $i(f)(\xi)$ for some $\xi < \eta \leq i_{0,n}(\delta)$. Each such ordinal

can be represented using $\delta, i_{0,1}(\delta), \dots, i_{0,n-1}(\delta)$ and therefore we may assume that $x = i(f)(\delta, i_{0,1}(\delta), \dots, i_{0,n-1}(\delta))$ since the critical point of $i_{n,\infty}$ is $i_{0,n}(\delta)$, we have that

$$x = i_{n,\infty}(i_{0,n}(f)(\delta, i_{0,1}(\delta), \dots, i_{0,n-1}(\delta))) \in \text{rng}(i_{n,\infty})$$

The other inclusion is similar. \square

Lemma 3.14. *Suppose $i : M \rightarrow N$ is an elementary embedding δ is a regular cardinal, and $\delta \leq \eta < i(\delta)$ is such that $\eta \in i(C)$ for every closed unbounded set $C \subseteq \delta$ in M . Let $X = \text{Hull}^N(i[M] \cup \eta)$, let $k : \bar{N} \rightarrow N$ be the inverse of the transitive collapse, and let $\bar{i} = k^{-1} \circ i$. Then $\bar{i}(\delta) = \eta$.*

Proof. Since k^{-1} is just the transitive collapse, it suffices to prove that there are no ordinals $\alpha \in X$ between η and $i(\delta)$. Let $\alpha \in X$ be below $i(\delta)$. Then by $\alpha = i(f)(\xi)$ for some $\xi < \eta$. We may assume that $f : \delta \rightarrow \delta$. Let $C_f \subseteq \delta$ be the club of closure points of f . Then the assumption of the Lemma, $\eta \in i(C_f)$, namely, η is a closure point of $i(f)$. Since $\xi < \eta$, $\alpha = i(f)(\xi) < \eta$. Hence no ordinal in X is between η and $i(\delta)$. \square

A filter on ρ extending the tail filter on ρ is called *fine*.

Lemma 3.15. *Suppose M is a transitive model of set theory, $i : M \rightarrow N$ is the complete iteration of \vec{U} in M , U is a normal M -ultrafilter on δ , where δ is the minimal element in $\text{dom}(\vec{U})$, and \tilde{U} is a fine N -ultrafilter on an ordinal $\eta \leq i(\delta)$ extending $\{i(A) \cap \eta : A \in U\}$. Then one of the following holds:*

- $\{i_{0n}(\delta)\} \in \tilde{U}$ for some $n < \omega$,
- $\tilde{U} = i_{0n}(U)$ for some $n \leq \omega$.

Proof. If $\eta = \nu + 1$ is a successor ordinal, then since \tilde{U} is fine, $\{\nu\} \in \tilde{U}$. In that case, for every $A \in U$, $\nu \in i(A)$. Note that since the critical point of $i_{\omega,\infty}$ is greater than $i_{0,\omega}(\delta)$, $i_{0,\omega}(A) = i(A)$. Since $i_{0,\omega}$ is the ω^{th} iterate of the normal measure U_δ , the only seeds for a normal ultrafilter in $i_{0,\omega}$ are the $i_{0,n}(\delta)$ 's³, hence $\nu = i_{0n}(\delta)$ for some $n < \omega$.

Now assume that η is a limit ordinal. Since \tilde{U} is fine, every set in \tilde{U} is unbounded in η . It follows that for every closed unbounded set $C \subseteq \delta$ in M , $i(C) \cap \eta$ is unbounded in η , and therefore if $\eta < i(\delta)$, then $\eta \in i(C)$. Let $X = \text{Hull}^N(i[M] \cup \eta)$, let $k : \bar{N} \rightarrow N$ be the inverse of the transitive collapse of X , and let $\bar{i} = k^{-1} \circ i$.

³If W is a normal ultrafilter derived from $i_{0,\omega}$ using α , then W is derived from $i_{0,n}$ and α' for some $n < \omega$ and some α' such that $i_{n+1,\omega}(\alpha') = \alpha$. Therefore $W \leq_{RK} U_\delta^n$. But then $W \equiv_{RK} U^m$ for some $m \leq n$ (see for example [2, Lemma 2.4]). Since W is normal, $m = 1$ and $W = U$, and again by normality, the only RK-projections of U^n onto U are given by the coordinate projections. Equivalently, the only seeds α for U from j_{U^n} are $\{i_{0,m}(\delta) \mid m < n\}$.

Note that $\bar{i} : M \rightarrow \bar{N}$, $\bar{N} = \text{Hull}^{\bar{N}}(\bar{i}[M] \cup \eta)$, and $\bar{i}(\delta) = \eta$ by Lemma 3.14⁴. Lemma 3.12 implies that $F \cup \bar{i}[U]$ generates $\bar{i}(U)$, where F denotes the tail filter on η . Since \tilde{U} is fine, $F \subseteq \tilde{U}$, and $\bar{i}[U] = \{i(A) \cap \eta : A \in U\} \subseteq \tilde{U}$. Since $F \cup \bar{i}[U]$ generates $\bar{i}(U)$, it follows that $\bar{i}(U) \subseteq \tilde{U}$.

By Lemma 3.13, there is some $n \leq \omega$ such that $\bar{i} = i_{0n}$ and $k = i_{n\infty}$. Since $k = i_{n\infty}$ and $\eta \leq \text{crit}(k)$, we have $P(\eta) \cap \bar{N} = P(\eta) \cap N$, and therefore using the maximality of ultrafilters and the fact that $\bar{i}(U) \subseteq \tilde{U}$, we obtain $\bar{i}(U) = \tilde{U}$. Since $\bar{i} = i_{0n}$, we have $\tilde{U} = \bar{i}(U) = i_{0n}(U)$, which proves the lemma. \square

4. SOME ULTRAFILTERS IN THE DISCRETE MAGIDOR EXTENSION

Throughout this section, we fix a measurable cardinal κ , a discrete set of measurable cardinals $\Delta \subseteq \kappa$ such that $\sup(\Delta) = \kappa$, a sequence $\vec{U} = \langle U_\delta : \delta \in \Delta \rangle$ of normal ultrafilters U_δ on δ , and a V -generic filter G on the discrete Magidor product \mathbb{P}_κ associated with \vec{U} . This section is devoted to showing that Kaplan's theorem (Corollary 3.8) does not generalize to arbitrary κ -complete ultrafilters on κ .

4.1. An ultrafilter with infinitely many extensions. In this subsection, we exhibit a κ -complete ultrafilter W on $\kappa \times \kappa$ that, in $V[G]$, has infinitely many distinct extensions to κ -complete ultrafilters.

Before we do this, let us make some general comments on where ultrafilters in $V[G]$ come from. Let \tilde{W} be a $V[G]$ -ultrafilter. Then \tilde{W} is uniquely determined by the following three ingredients:

- $j_{\tilde{W}}^{V[G]} \upharpoonright V$, the *restricted ultrapower embedding*
- $j_{\tilde{W}}(G)$, the *image generic*
- $[\text{id}]_{\tilde{W}}$, the *seed*

The first two ingredients determine $j_{\tilde{W}}^{V[G]}$ and given that $[\text{id}]_{\tilde{W}} = a$, we can recover \tilde{W} as the ultrafilter derived from $j_{\tilde{W}}^{V[G]}$ and a .

Note that an arbitrary list of ingredients need not form a recipe for cooking up a genuine $V[G]$ -ultrafilter. Suppose one is given an elementary embedding $j : V \rightarrow M$, an M -generic filter H on $j(\mathbb{P}_\kappa)$ and a point $a \in M$. When is there a $V[G]$ -ultrafilter \tilde{W} whose restricted ultrapower is j , image generic is H , and seed a ? It is easy to see this is the case if and only if the following hold:

- $j[G] \subseteq H$.
- $M \subseteq \text{Hull}^{M[H]}(j[V] \cup \{H, a\})$.

⁴Although in Lemma 3.14 we are assuming that $\eta < i(\delta)$, the conclusion $\eta = \bar{i}(\delta)$ is true also when $\eta = i(\delta)$. To see this, note that in this case $i(\delta) + 1 \subseteq X$ and therefore $\bar{i}(\delta) = k^{-1}(i(\delta)) = i(\delta) = \eta$.

We use here Corollary 2.3 which sets up an equivalent condition for an embedding $k : V[G] \rightarrow M$ being an ultrapower embedding by some $V[G]$ -ultrafilter \tilde{W} .

Let us turn to the description of the ultrafilter W with infinitely many extensions to $V[G]$. We start with any normal ultrafilter D on κ . For each $\alpha < \kappa$, let

$$\delta(\alpha) = \min(\Delta \setminus \alpha)$$

and let

$$W = \sum_D U_{\delta(\alpha)}$$

In other words, a set $A \subseteq \kappa \times \kappa$ belongs to W if and only if for D -almost all α , for $U_{\delta(\alpha)}$ -almost all β , $(\alpha, \beta) \in A$. The well-known general analysis of sums of ultrafilters yields the following lemma (see for example [6, 3.5.7]):

Lemma 4.1. *Let $\delta = \min(j_D(\Delta) \setminus \kappa)$ and let $U = j_D(\vec{U})_\delta$. Then $V_W = (V_D)_U$, $j_W = j_U \circ j_D$, and $[id]_W = (\kappa, \delta)$.*

A $V[G]$ -ultrafilter \tilde{W} given by the three ingredients extends W if there is an elementary embedding $k : V_W \rightarrow j_{\tilde{W}}(V)$ such that the restricted ultrapower $j_{\tilde{W}}^{V[G]} \upharpoonright V$ is equal to $k \circ j_W$ and k maps $[id]_W$ to $[id]_{\tilde{W}}$.

The first lift is the canonical extension W^* (see Definition 3.6), whose three ingredients are $i^W \circ j_W$, $G \times G_{\vec{s}^W}$ and (κ, δ) . Here

$$i^W : V_W \rightarrow N$$

is the complete iteration of V_W by $j_W(\vec{U}) \upharpoonright (\kappa, j_W(\kappa))$. (Note that the critical point of i^W is above δ .)

To define a non-canonical lift of W , we will absorb j_U into the complete iteration i^D . Formally, let $i^D : V_D \rightarrow N'$ be the complete iteration of V_D via $j_D(\vec{U}) \upharpoonright (\kappa, j_D(\kappa))$. Since U is the first ultrafilter used in the complete iteration of $j_D(\vec{U}) \upharpoonright (\kappa, j_D(\kappa))$, it is easy to see that $N' = N$ and

$$i^D = i^W \circ j_U.$$

Let $\Delta^N = i^D(\Delta)$, and let $\vec{s}^D = \langle s_\alpha^D : \alpha \in \Delta^N \setminus \kappa \rangle$ be the associated sets of indiscernibles. By Proposition 3.7, letting D^* be the canonical extension of D , $j_{D^*}^{V[G]} \upharpoonright V = i^D \circ j_D$ and $j_{D^*}^{V[G]}(G) = G \times G_{\vec{s}^D}$.

Observe that

$$i^W \circ j_W = i^W \circ j_U \circ j_D = i^D \circ j_D$$

Similarly, letting $\vec{s}^W = \langle s_\alpha^W : \alpha \in \Delta^N \setminus \kappa \rangle$ denote the associated sequence of sets of indiscernibles and $\delta^* = i^D(\delta)$, we have

$$s_\alpha^D = \begin{cases} s_\alpha^W & \text{if } \alpha \neq \delta^* \\ s_{\delta^*}^W \cup \{\delta\} & \text{if } \alpha = \delta^* \end{cases}$$

It follows that $j_{D^*} \neq j_{W^*}$ since

$$j_{W^*}(G) = G \times G_{\vec{s}^W} \neq G \times G_{\vec{s}^D} = j_{D^*}(G)$$

yet

$$V[G]_{W^*} = N[G \times G_{\bar{s}W}] = N[G \times G_{\bar{s}D}] = V[G]_{D^*}.$$

Now let W' be the $V[G]$ -ultrafilter on $\kappa \times \kappa$ derived from j_{D^*} using (κ, δ) . Then by Corollary 2.3 $j_{W'} = j_{D^*}$. To see that W' lifts W , we note that $j_{D^*} \upharpoonright V = i^D \circ j_W = i^W \circ j_W$ and again $i^W(\kappa, \delta) = (\kappa, \delta)$. So the three ingredients of W' are $i^W \circ j_W$, $G \times G_{\bar{s}D}$, and (κ, δ) . As we noted above, $j_{D^*}(G) \neq j_{W^*}(G)$ and it follows that $W' \neq W^*$.

Thus we have constructed two distinct $V[G]$ -ultrafilters extending W : the canonical one, and another that is Rudin-Keisler equivalent to D^* . Are these the only extensions? As the title of this subsection suggests, the answer is no and there are infinitely many more, falling into two countably infinite families: the first generalizing W' and the second generalizing W^* . We begin with the generalizations of W' , which are a bit easier to describe as they are all Rudin-Keisler equivalent to D^* . Let $\langle \delta_n \rangle_{n < \omega}$ be the increasing enumeration of $s_{\delta^*}^D$, the set of indiscernibles associated with δ^* in the complete iteration of V_D .

Definition 4.2. Let W_n^1 be the $V[G]$ -ultrafilter derived from $j_{D^*}^{V[G]}$ using (κ, δ_n) .

The reason this forms an extension of W is that we can represent $i^W \circ j_W$ differently. It is a well-known fact that $j_{U^{n+1}} = j_{j_{U^n}(U)} \circ j_{U^n} = (j_{U^n} \upharpoonright V_U) \circ j_U$. Therefore

$$\begin{aligned} i^W \circ j_W &= i^D \circ j_D \\ &= i_{n+1, \theta}^D \circ j_{U^{n+1}} \circ j_D \\ &= i_{n+1, \theta}^D \circ (j_{U^n} \upharpoonright V_U) \circ j_U \circ j_D \\ &= i_{n+1, \theta}^D \circ (j_{U^n} \upharpoonright V_U) \circ j_W \end{aligned}$$

Once again it is not hard to see that Corollary 2.3 can be applied here to conclude that for every $n < \omega$, $j_{W_n^1}^{V[G]} = j_{D^*}^{V[G]}$ and $[\text{id}]_{W_n^1} = (\kappa, \delta_n)$. In other words, the three ingredients that determine W_n^1 are $i_{n+1, \theta}^D \circ j_{U^n} \upharpoonright M_U \circ j_W$, $G \times G_{\bar{s}D}$, and (κ, δ_n) . Note that $i_{n+1, \theta}^D(j_{U^n}(\kappa, \delta)) = (\kappa, j_{U^n}(\delta)) = (\kappa, \delta_n)$ and therefore W_n^1 lifts W . All the W_n^1 's are distinct as they are derived from the same normal ultrapower embedding (i.e., they are Rudin-Keisler equivalent) using different seeds.

We now turn to the second family of extensions of W : the generalizations of W^* , which will be denoted by W_n^0 . We specify the ultrafilter W_n^0 by listing the three ingredients first. As in the case of W_n^1 , the restricted ultrapower embedding associated with W_n^0 is $i^D \circ j_D$ and the seed is (κ, δ_n) . The difference is in the image generic: we will have $j_{W_n^0}(G) \neq G \times G_{\bar{s}D}$. Instead,

$$j_{W_n^0}(G) = G \times G_{\bar{s}^n}$$

where \vec{s}^n is the sequence of sets of indiscernibles obtained from \vec{s}^D by removing the ordinal δ_n from $s_{\delta^*}^D$; that is, $s_{\delta^*}^n = s_{\delta^*}^D \setminus \{\delta_n\}$ and for $\alpha > \delta^*$, $s_\alpha^n = s_\alpha^D$.

It is not entirely obvious that there is an extension of W to a $V[G]$ -ultrafilter that has this restricted ultrapower embedding, image generic, and seed. To show that W_n^0 exists, we need to prove that there is an elementary embedding $\ell : V[G] \rightarrow N[G \times G_{\vec{s}^n}]$ extending $i^W \circ j_W$ such that $\ell(G) = G \times G_{\vec{s}^n}$ and

$$(1) \quad N[G \times G_{\vec{s}^n}] = \text{Hull}^{N[G \times G_{\vec{s}^n}]}(\ell[V[G]] \cup \{(\kappa, \delta_n)\})$$

Then by Corollary 2.3, $\ell = j_{W_n^0}$ where W_n^0 is the $V[G]$ -ultrafilter on $\kappa \times \kappa$ derived from ℓ using (κ, δ_n) .

To show that ℓ exists, let U_n denote the n -th iterate $j_{U^n}(U)$ of U , and note that U_n is an $N[G_{\vec{s}^D}]$ -ultrafilter on δ_n , although U_n is not an element of $N[G_{\vec{s}^D}]$. By Lévy-Solovay, U_n generates an $N[G \times G_{\vec{s}^D}]$ -ultrafilter U_n^* and $j_{U_n^*} \restriction N[G_{\vec{s}^D}] = j_{U_n}^{N[G_{\vec{s}^D}]}$. We will set

$$(2) \quad \ell = j_{U_n^*} \circ j_{D^*}$$

By Proposition 3.5 applied in V_D , $j_{U_n}^{N[G_{\vec{s}^D}]} \circ i^D = i^D$, and therefore

$$\ell \restriction V = j_{U_n^*} \circ j_{D^*} \restriction V = (j_{U_n^*} \restriction N[G_{\vec{s}^D}]) \circ (i^D \circ j_D) = i^D \circ j_D.$$

Namely ℓ extends $i^D \circ j_D$; moreover, Proposition 3.5 ensures that $j_{U_n}(G_{\vec{s}}) = G_{\vec{s}^n}$, and combining with Proposition 3.7 we have that

$$\ell(G) = j_{U_n^*}(j_{D^*}(G)) = j_{U_n^*}(G \times G_{\vec{s}}) = G \times G_{\vec{s}^n}.$$

This verifies that ℓ has the correct restricted embedding and image generic.

Finally, we verify (1). Let $H = \text{Hull}^{N[G \times G_{\vec{s}}]}(\ell[V[G]] \cup \{(\kappa, \delta_n)\})$. Since $N[G \times G_{\vec{s}}] = V[G]_{D^*}$, we have

$$N[G \times G_{\vec{s}}] = \text{Hull}^{N[G \times G_{\vec{s}}]}(j_{D^*}[V[G]] \cup \{\kappa\})$$

To show $N[G \times G_{\vec{s}}] = H$, it therefore suffices to show that $j_{D^*}[V[G]]$ is contained in H . For this, since $j_{D^*} \restriction V = \ell \restriction V$, it is enough to show that $j_{D^*}(G) \in H$. But $j_{D^*}(G) = G \times G_{\vec{s}}$ is definable from $\ell(G) = G \times G_{\vec{s}^n}$ and δ_n , as, roughly speaking, $G_{\vec{s}} = G_{\vec{s}^n} \cup \{\delta_n\}$. Since $j_{D^*}(G)$ is definable from parameters in H , it belongs to H .

Remark 4.3. Note that we defined the extension W_n^0 essentially by removing a single ordinal from \vec{s}^D , to obtain \vec{s}^n . One might be tempted to define other similar extensions of W , instead using sequences \vec{t} obtained by removing more elements of \vec{s}^n . But in fact, using such a sequence \vec{t} in our specification of the three ingredients that constitute a lift of W would be fallacious, because these ingredients do not correspond to any ultrafilter in $V[G]$. The reason is that removing any element of \vec{s}^D other than δ_n makes Equation (1) above *false*.

We note the following theorem, which follows from the foregoing analysis of W_1^0 :

Theorem 4.4. *In $V[G]$, for any normal ultrafilter F on κ , there is a non-trivial elementary embedding from $V[G]_F$ to itself.*

Proof. By Kaplan's theorem (Corollary 3.8), $F = D^*$ for some normal ultrafilter D of V . As above, let $U = j_D(\vec{U})_{\delta^*}$ and let U^* be the $V[G]_{D^*}$ -ultrafilter generated by U . Then $(V[G]_{D^*})_{U^*} = V[G]_{D^*}$, and so $j_U : V[G]_{D^*} \rightarrow V[G]_{D^*}$ is a nontrivial elementary embedding. \square

4.2. Classifying the extensions of W . In this section, we prove the special case of our classification of ultrafilters in $V[G]$ for the ultrafilter $W = \sum_D U_{\delta(\alpha)}$.

Theorem 4.5. *If \bar{W} is a countably complete $V[G]$ -ultrafilter extending W , then $\bar{W} = W_n^i$ for some $i \in \{0, 1\}$ and $n < \omega$.*

This proof contains most of the key ideas of the classification and avoids some notational difficulties involved in propagating the result to arbitrary ultrafilters.

Proof. Let \bar{W} be an extension of W to a $V[G]$ -ultrafilter. Since \bar{W} extends W , the Rudin-Keisler projection of $(\pi_0)_*(\bar{W})$ of \bar{W} using π_0 extends D , where $\pi_0 : \kappa \times \kappa \rightarrow \kappa$ denotes the projection to the first coordinate. By Kaplan's theorem (Corollary 3.8), it follows that $(\pi_0)_*(\bar{W})$ must be equal to D^* . Therefore there is an elementary embedding $k : V[G]_{D^*} \rightarrow V[G]_{\bar{W}}$ such that $k \circ j_{D^*} = j_{\bar{W}}$ and $k(\kappa) = \kappa$.

Note that $[id]_{\bar{W}} = (\kappa, \bar{\delta})$ for some ordinal $\bar{\delta} > \kappa$. Let η be the least ordinal such that $k(\eta) > \bar{\delta}$ and let \bar{U} denote the $V[G]_{D^*}$ -ultrafilter on η derived from k using $\bar{\delta}$. By Corollary 2.3, $k = j_{\bar{U}}$ and $[id]_{\bar{U}} = \bar{\delta}$.

Claim 4.6. *For some $n < \omega$, $\bar{\delta} = \delta_n$ and either $\bar{U} = U_n^*$ or $\{\delta_n\} \in \bar{U}$, so \bar{U} is principal.*

Here U_n^* is defined as in the paragraph preceding (2). Granting this claim, it is easy to see that either $\bar{W} = W_n^0$ or $\bar{W} = W_n^1$. Indeed if $\{\delta_n\} \in \bar{U}$ then $j_{\bar{U}}$ is the identity and $j_{\bar{W}} = j_{D^*}$. Then \bar{W} is derived from j_{D^*} using (κ, δ_n) which is by definition the ultrafilter W_n^0 . If $\bar{U} = U_n^*$, then \bar{W} is derived from $j_{U_n^*} \circ j_{D^*}$ using (κ, δ_n) , which is by definition W_n^0 .

To prove the claim, we analyze the N -ultrafilter $\tilde{U} = \bar{U} \cap N$. We will show that for some n , either $\tilde{U} = U_n$ or $\{\delta_n\} \in \tilde{U}$. The claim then follows since in either case, \tilde{U} generates an $N[G \times G_{\bar{s}}]$ -ultrafilter.

The analysis of \tilde{U} is an application of Lemma 3.15 in the case $M = V_D$ and $i = i^D$, which implies that either \tilde{U} has the desired form or else $\tilde{U} = i_{0\omega}^D(U)$. But the latter cannot occur, because \tilde{U} extends to a countably complete $V[G]_{D^*}$ -ultrafilter (namely, \bar{U}), whereas $i_{0\omega}^D(U)$ does not since $i_{0\omega}^D(\delta)$ has countable cofinality in $V[G]_{D^*}$. $\square_{\text{Theorem 4.5}}$

4.3. Some other ultrafilters. We describe a slight variant of the classification from the previous section when the second ultrafilter in the sum does not come from the image of \vec{U} . We start with any normal ultrafilter D on κ . For each $\alpha < \kappa$, let

$$\delta(\alpha) = \min(\Delta \setminus \alpha)$$

and let $Z_{\delta(\alpha)} \neq U_{\delta(\alpha)}$ be a normal measure on $\delta(\alpha)$.⁵ Let

$$W = \sum_D Z_{\delta(\alpha)}$$

Again, one lift of W is the canonical extension W^* .

In this case there is no analog of the ultrafilter W' considered in Section 4.1 since $Z = [\alpha \mapsto Z_{\delta(\alpha)}]_D$ cannot be absorbed into i^D : the first ultrafilter applied in i^D is $U \neq Z$.

However, we still have the analogues of the ultrafilters W_n^0 . Indeed, let us specify the ultrafilter W_n^0 in this case by listing the three ingredients. The major difference is the restricted ultrapower embedding associated with W_n^0 , which is no longer equal to $i^W \circ j_W$. Instead, the restricted ultrapower embedding is $i^{j_{U^n}(j_W(\vec{U}))} \circ j_{U^n} \circ j_W$ and the seed is (κ, δ_n) where as before $\delta_n = j_{U^n}(\delta)$. The image generic: we will have $j_{W_n^0}(G) = G \times G_{\vec{s}^n}$ where \vec{s}^n is defined as follows: let \vec{r} be the sequence of sets of indiscernibles obtained by the complete iteration of $j_{U^n}(j_W(\vec{U}))$ and let \vec{s}^n be the sequence obtained by adding $\delta_0, \dots, \delta_{n-1}$ to \vec{r} .

The proof that these three ingredients constitute a valid lift of W is as in the previous sections, as is the proof that the ultrafilters W_n^0 exhaust all lifts of W to $V[G]$.

5. CLASSIFICATION OF ULTRAFILTERS IN THE MAGIDOR EXTENSION

Let Δ be a discrete set of measurable cardinals with supremum κ , and let $\vec{U} = \langle U_\alpha : \alpha \in \Delta \rangle$ be a sequence of normal measures U_α on α . Our goal in this section is to classify the extensions of sums of normal ultrafilters to $V[G]$ where $G \subseteq \mathbb{P}_\kappa$ is V -generic for the Magidor iteration of \vec{U} . We begin with Section 5.1 by defining a family of extensions of a given sum of normal ultrafilters and analyzing the relationship between their ultrapowers. Then in Section 5.2, we show that this family exhausts all extensions of the sum.

5.1. Extensions of an iterated sum of normal ultrafilters.

Definition 5.1. Let M be a transitive model of set theory.

- A *finite iteration* of M is a sequence $(D_m : m < n)$ such that for each $m < n$, D_m is a $M_{D_0, \dots, D_{m-1}}$ -ultrafilter.

⁵Under UA, the existence of distinct normal measures on κ implies $o(\kappa) \geq 2$, so the situation described here cannot occur unless $\delta(\alpha)$ is a limit of measurable cardinals. Since we are considering discrete sequences \vec{U} , it is reasonable to consider the case where no element of \vec{U} is a limit of measurables.

- Let $M_m = M_{D_0, \dots, D_{m-1}}$ and $j_{m_0 m_1} : M_{m_0} \rightarrow M_{m_1}$ be the iterated ultrapower embedding $j_{D_{m_0} \dots D_{m_1-1}}$.
- An iteration is *internal* if for each $m < n$, $D_m \in M_m$.
- An iteration is *normal* if for each $m < n$, D_m is a M_m -normal ultrafilter on δ_m and $\delta_0 < \delta_1 < \dots < \delta_{n-1}$.

We say that an iteration (D_0, \dots, D_{n-1}) is *below* an ordinal γ if for each $m < n$, D_m is an ultrafilter on $\delta_m < j_{D_0, \dots, D_{m-1}}(\gamma)$.

Definition 5.2. The *sum* of a normal iteration (D_0, \dots, D_{n-1}) , denoted $\Sigma(D_0, \dots, D_{n-1})$, is the unique ultrafilter W on κ^n such that $j_W = j_{D_0, \dots, D_{n-1}}$ and $[id]_W = (\delta_0, \delta_1, \dots, \delta_{n-1})$, where κ is least such that (D_0, \dots, D_{n-1}) is below κ .

The following theorem [6, Theorems 5.3.8 and 5.3.13] explains why it is natural to consider such sums in our classification:

Theorem 5.3 (UA). *Assume that there is no cardinal κ with $o(\kappa) = 2^{2^\kappa}$. Then every countably complete ultrafilter is Rudin-Keisler equivalent to the sum of a normal iteration.*

Fix an internal iteration (D_0, \dots, D_{n-1}) of normal ultrafilters. Our plan is to classify all extensions of $\Sigma(D_0, \dots, D_{n-1})$ to $V[G]$ where $G \subseteq \mathbb{P}_\kappa$ is V -generic. The first step is to define a countable family $\{\Sigma(D_0, \dots, D_{n-1})_x^u\}_{u,x}$ of extensions of $\Sigma(D_0, \dots, D_{n-1})$, associated to some finite parameters u, x .

Let d be the set of $m \leq n$ such that $\delta_m \in j_{0m}(\Delta)$, and let d' be the set of $m \in d$ such that $D_m = j_{0m}(\vec{U})_{\delta_m}$.

We will associate to each $u : d' \rightarrow \{0, 1\}$ and $x : d \rightarrow \omega$ an extension $\Sigma(D_0, \dots, D_{n-1})_x^u$ of $\Sigma(D_0, \dots, D_{n-1})$. Let us briefly explain the role of these parameters in terms of the three ingredients that determine the extension $\bar{W} = \Sigma(D_0, \dots, D_{n-1})_x^u$. (The “three ingredients” framework is introduced Section 4.1.) Note that the seed $[id]_{\bar{W}}$ has the form $(\tilde{\delta}_0, \dots, \tilde{\delta}_{n-1})$. The number $u(\delta_m) \in \{0, 1\}$ will determine whether or not $\tilde{\delta}_m$ is a Prikry point in the image generic $j_{\bar{W}}(G)$. The number $x(\delta_m) < \omega$ determines how many Prikry points are below $\tilde{\delta}_m$ in the first Prikry sequence above $\tilde{\delta}_m$.

By recursion on $m \leq n$, we define a $V[G]$ -ultrafilter $\bar{W}_m = \Sigma(D_0, \dots, D_{m-1})_x^u$ extending $W_m = \Sigma(D_0, \dots, D_{m-1})$. We will also define an external iteration $(E_0, E_1, \dots, E_{m-1})$ of V_{W_m} below δ_m whose well-founded last model P_m completely iterates into $j_{\bar{W}_m}^{V[G]}(V)$. More precisely,

- Let $e_m : V_{W_m} \rightarrow P_m$ be the iterated ultrapower by (E_0, \dots, E_{m-1}) .
- Let $i^{P_m} : P_m \rightarrow N_m$ be the complete iteration of P_m by $e_m(j_{W_m}(\vec{U}))$ above κ .

We will maintain that the following hold:

- $N_m = j_{\bar{W}_m}(V)$
- $j_{\bar{W}_m} \upharpoonright V = i^{P_m} \circ e_m \circ j_{W_m}$
- $i^{P_m} \circ e_m([id]_{W_m}) = [id]_{\bar{W}_m}$

This ensures, in particular, that the ultrafilter \overline{W}_m lifts W_m .

Fix $m < n$ and assume that we have already defined \overline{W}_m and the associated external iteration (E_0, \dots, E_{m-1}) satisfying the bullets above. We will define \overline{W}_{m+1} and E_m and show in Claim 5.5 that our recursive hypotheses are maintained.

Let $i : V_{W_m} \rightarrow N_m$ be the composition $i^{P_m} \circ e_m$. We will define an N_m -ultrafilter \tilde{D}_m extending

$$\{i(A) \cap \eta : A \in D_m\}$$

for some $\eta \leq i(\delta_m)$. The ultrafilter \tilde{D}_m will generate a $V[G]_{\overline{W}_m}$ -ultrafilter, which we denote by $D_m^{u,x}$, and we will set $\overline{W}_{m+1} = \Sigma(\overline{W}_m, D_m^{u,x})$. Therefore in the end we will have $\overline{W}_n = \Sigma(D_0^{u,x}, \dots, D_{n-1}^{u,x})$.

If $m \notin d$, $\tilde{D}_m = i(D_m)$ and E_m is the principal P_m -ultrafilter concentrated at $e_m(\delta_m)$.

Now suppose $m \in d$, in which case \tilde{D}_m will depend on u and x . Define E_m to be the external ultrafilter $e_m(j_{W_m}(\vec{U})_{\delta_m})^{x(m)}$. For each β less than the length of the complete iteration of P_m , let $\delta_m^\beta = i_{0\beta}^{P_m}(e_m(\delta_m))$ and $D_m^\beta = i_{0\beta}^{P_m}(e_m(D_m))$.

Let α be the first stage of the complete iteration of P_m such that $\text{crit}(i_{\alpha\alpha+1}^{P_m}) = \delta_m^\alpha$. If $m \in d'$ and $u(m) = 1$, let \tilde{D}_m be the principal ultrafilter concentrated at $\delta_m^{\alpha+x(m)}$. Otherwise, let $\tilde{D}_m = D_m^{\alpha+x(m)}$.

We have $\{i(A) \cap \eta : A \in D_m\} \subseteq \tilde{D}_m$ where

$$\eta = \begin{cases} i(\delta_m) & \text{if } m \notin d \\ \delta_m^{\alpha+x(m)} + 1 & m \in d' \text{ and } u(m) = 1 \\ \delta_m^{\alpha+x(m)} & \text{otherwise} \end{cases}$$

Claim 5.4. \tilde{D}_m generates a $V[G]_{\overline{W}_m}$ -ultrafilter $D_m^{u,x}$

Proof. The proof is by cases. In the first case when $m \notin d$ we appeal to Theorem 2.13. In the second case, when $m \in d'$ and $u(m) = 1$, \tilde{D}_m is principal and therefore trivially generates a $V[G]_{\overline{W}_m}$ -ultrafilter. In the last case, \tilde{D}_m is a γ -complete N_m -ultrafilter on $\gamma = \delta_m^{\alpha+x(m)}$, so it generates an ultrafilter by Lévy-Solovay. \square

Finally, define

$$\overline{W}_{m+1} = \Sigma(\overline{W}_m, D_m^{u,x}).$$

To complete the induction, we must prove the following claim:

Claim 5.5. $N_{m+1} = j_{\overline{W}_{m+1}}(V)$, $j_{\overline{W}_{m+1}} \upharpoonright V = i^{P_{m+1}} \circ e_{m+1} \circ j_{W_{m+1}}$, and $i^{P_{m+1}} \circ e_{m+1}([id]_{W_{m+1}}) = [id]_{\overline{W}_{m+1}}$.

Proof. We consider the three cases. For the first case, assume $m \notin d$. Let G_m be the N_m -generic filter given by the sequence of sets of indiscernibles associated with the complete iteration i^{P_m} . By the induction hypothesis,

$V[G]_{\overline{W}_m} = N_m[G \times G_m]$. By definition, in this case, $\tilde{D}_m = i(D_m)$. Let D_m^* be the $N_m[G_m]$ -ultrafilter generated by \tilde{D}_m .

$$\begin{array}{ccc}
V[G]_{\overline{W}_m} & \xrightarrow{D_m^{u,x}} & V[G]_{\overline{W}_{m+1}} \\
\cup & & \cup \\
N_m[G_m] & \xrightarrow{D_m^*} & N_{m+1}[G_{m+1}] \\
\cup & & \cup \\
N_m & \xrightarrow{j_{D_m^0} \upharpoonright N_m} & N_{m+1} \\
\uparrow i_{\alpha,\infty}^{P_m} & & \uparrow i_{j_{D_m^0}(\alpha),\infty}^{P_{m+1}} \\
j_{D_m^0} \upharpoonright N_{m,\alpha} & \nearrow & N_{m+1, j_{D_m^0}(\alpha)} \\
N_{m,\alpha} & \xrightarrow{D_m^\alpha} & N_{m+1,\alpha} \\
\uparrow i_{0,\alpha}^{P_m} & & \uparrow i_{0,\alpha}^{P_{m+1}} \\
P_m & \xrightarrow{D_m^0} & P_{m+1} \\
\uparrow e_m & & \uparrow e_{m+1} \\
V_{W_m} & \xrightarrow{D_m} & V_{W_{m+1}}
\end{array}$$

FIGURE 2. The case that $m \notin d$

Note that by Lévy-Solovay,

$$j_{D_m^{u,x}} \upharpoonright N_m[G_m] = j_{D_m^*}^{N_m[G_m]}$$

The key point is that

$$(3) \quad j_{D_m^*}^{N_m[G_m]} \upharpoonright N_m = j_{D_m^0} \upharpoonright N_m$$

To see this, let α be the least ordinal such that $\text{crit}(i_{\alpha,\alpha+1}^{P_m}) > e_m(\delta_m)$ and consider the model $N_{m,\alpha}[G_m \upharpoonright \delta_m^0]$. Note that $G_m \upharpoonright \delta_m^0$ is $N_{\alpha,m}$ -generic for a forcing which has smaller cardinality than the critical point of the embedding $i_{\alpha,\infty}^{P_m}$. So by the Lévy-Solovay argument, $i_{\alpha,\infty}^{P_m}$ lifts to an embedding $i_{\alpha,\infty}^* : N_{m,\alpha}[G_m \upharpoonright \delta_m^0] \rightarrow N_m[G_m \upharpoonright \delta_m^0]$. It is easy to see that $i_{\alpha,\infty}^*$ is the complete iteration of $N_{m,\alpha}[G_m \upharpoonright \delta_m^0]$ via the canonical lift of the sequence $i_{0\alpha}^{P_m}(e_m(\vec{U})) \upharpoonright (\delta_m^0, \infty)$. Moreover $N_m[G_m]$ is the generic extension of the final model of this iteration by the filter obtained from the associated sequence of sets of indiscernibles. Therefore we can apply Lemma 3.4 in $N_{m,\alpha}[G_m \upharpoonright \delta_m^0]$ to conclude that $N_m[G_m]$ is closed under δ_m^0 -sequences from $N_{m,\alpha}[G_m \upharpoonright \delta_m^0]$.

Note that

$$(4) \quad j_{D_m^\alpha} \circ i_{0,\alpha}^{P_m} = i_{0,\alpha}^{P_{m+1}} \circ j_{D_m^0}.$$

This follows once we prove that $i_{0,\alpha}^{P_{m+1}} = i_{0,\alpha}^{P_m} \upharpoonright P_{m+1}$. This is a routine induction on $\beta \leq \alpha$ using that $\text{crit}(j_{D_m^0})$ is greater than all the measurable cardinals appearing in the iteration $i_{0,\alpha}^{P_m}$.

By Mitchell's lemma (Lemma 3.10) applied in P_m with $W = D_m^0$,

$$j_{D_m^*}^{N_{m,\alpha}[G_m \upharpoonright \delta_m^0]} = j_{D_m^0} \upharpoonright N_{m,\alpha}[G_m \upharpoonright \delta_m^0].$$

Since $N_m[G_m]$ is closed under δ_m^0 -sequences from $N_{m,\alpha}[G_m \upharpoonright \delta_m^0]$, this implies that

$$(5) \quad j_{D_m^*}^{N_m[G_m]} = j_{D_m^*}^{N_{m,\alpha}[G_m \upharpoonright \delta_m^0]} \upharpoonright N_m[G_m] = j_{D_m^0} \upharpoonright N_m[G_m]$$

which proves (3).

By definition of e_{m+1} , $e_{m+1} = e_m \upharpoonright V_{W_{m+1}}$ ensuring that

$$j_{D_m^0} \circ e_m = e_{m+1} \circ j_{D_m}.$$

Also, $i^{P_{m+1}} = j_{D_m^0}(i^{P_m})$. We have

$$j_{D_m^{u,x}} \circ i^{P_m} = j_{D_m^*}^{N[G_m]} \circ i^{P_m} = j_{D_m^0} \circ i^{P_m} = i^{P_{m+1}} \circ j_{D_m^0}^{P_m}$$

Moreover

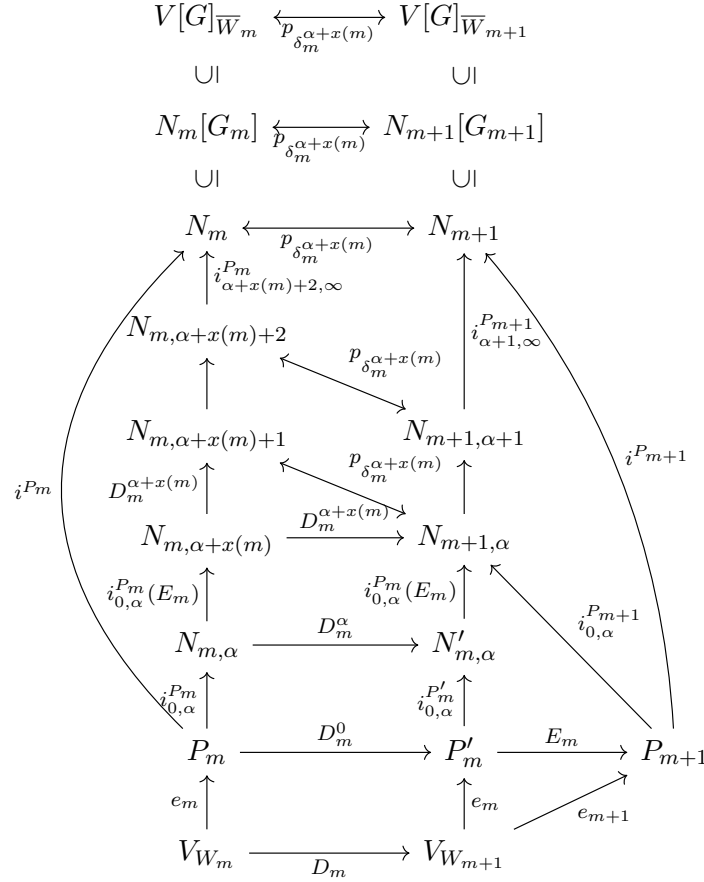
$$j_{D_m^0}^{P_m} \circ e_m = e_{m+1} \circ j_{D_m}$$

Combining these equations, we get

$$\begin{aligned} i^{P_{m+1}} \circ e_{m+1} \circ j_W &= i^{P_{m+1}} \circ e_{m+1} \circ j_{D_m} \circ j_{W_m} \\ &= i^{P_{m+1}} \circ j_{D_m^0}^{P_m} \circ e_m \circ j_{W_m} \\ &= j_{D_m^{u,x}} \circ i^{P_m} \circ e_m \circ j_{W_m} \\ &= j_{D_m^{u,x}} \circ j_{\bar{W}_m} \upharpoonright V \\ &= j_{\bar{W}_{m+1}} \upharpoonright V \end{aligned}$$

To finish the case $m \notin d$, by the normality of $D_m^{u,x}$, $[id]_{D_m^{u,x}}$ is the ordinal β over which $D_m^{u,x}$ is an ultrafilter. On the other hand, $i_{0,\alpha}^{P_{m+1}}(e_{m+1}(\delta_m)) = i_{0,\alpha}^{P_{m+1}}(e_m(\delta_m)) = \beta$. Hence $i_{0,\alpha}^{P_{m+1}}(e_{m+1}([id]_{W_{m+1}})) = [id]_{\bar{W}_{m+1}}$.

Next consider the case where $m \in d'$ and $u(m) = 1$. By definition \tilde{D}_m is $p_{\delta_m^{\alpha+x(m)}}$, the principal ultrafilter concentrated at $\delta_m^{\alpha+x(m)}$. The following diagram commutes:


 FIGURE 3. The case that $u(m) = 1$.

The commutativity of the second square from the bottom is proved as in Equation 4. The only other part of the diagram whose commutativity is not immediate is

$$i_{0,\alpha}^{P_{m+1}} \circ j_{E_m} = j_{i_{0,\alpha}^{P_m}(E_m)} \circ i_{0,\alpha}^{P'_m}$$

where $P'_m = e_m(V_{W_{m+1}})$ and $i_{0,\alpha}^{P'_m} : P'_m \rightarrow N'_{m,\alpha}$ is the α^{th} stage of the complete iteration of P'_m by $e_m(j_{W_{m+1}}(\vec{U}))$ above κ .

$$\begin{array}{ccc} N'_{m,\alpha} & \xrightarrow{i_{0,\alpha}^{P_m}(E_m)} & N_{m+1,\alpha} \\ i_{0,\alpha}^{P'_m} \uparrow & & \uparrow i_{0,\alpha}^{P_{m+1}} \\ P'_m & \xrightarrow{E_m} & P_{m+1} \end{array}$$

This commutativity is true since

$$j_{i_{0,\alpha}^{P_m}(E_m)}^{N'_{m,\alpha}} = j_{E_m} \upharpoonright N'_{m,\alpha} \text{ and } i_{0,\alpha}^{P_{m+1}} = j_{E_m}(i_{0,\alpha}^{P'_m}).$$

We include some details on how to show $j_{i_{0,\alpha}^{P_m}(E_m)}^{N'_{m,\alpha}} = j_{E_m} \upharpoonright N'_{m,\alpha}$. For this, we use that $j_{i_{0,\alpha}^{P_m}(E_m)}^{N'_{m,\alpha}} = j_{i_{0,\alpha}^{P_m}(E_m)}^{N_{m,\alpha}} \upharpoonright N'_{m,\alpha}$. Since $E_m \in P_m$, we can use Kunen's commuting ultrapowers lemma, as it appears in Woodin's [14, Lemma 3.30], to conclude that

$$j_{i_{0,\alpha}^{P_m}(E_m)}^{N_{m,\alpha}} = j_{E_m}^{P_m} \upharpoonright N_{m,\alpha}.$$

(We apply Woodin's lemma in P_m with $j = i_{0,\alpha}^{P_m}$ and $E = E_m$. Note that some of the generality of Woodin's lemma is not necessary here since j is definable over P_m rather than generic.)

Since $j_{\overline{W}_{m+1}} = j_{\overline{W}_m}$ then the commutativity of the diagram in Figure 3 can be used to deduce that

$$j_{\overline{W}_{m+1}} \upharpoonright V = j_{\overline{W}_m} \upharpoonright V = i^{P_m} \circ e_m \circ j_{W_m} = i^{P_{m+1}} \circ e_{m+1} \circ j_{W_{m+1}}.$$

In particular,

$$N_{m+1} = N_m = j_{\overline{W}_m}(V) = j_{\overline{W}_{m+1}}(V)$$

Finally, we show that $i^{P_{m+1}} \circ e_{m+1}([id]_{W_{m+1}}) = [id]_{\overline{W}_{m+1}}$. By the induction hypothesis it suffices to show that $i^{P_{m+1}}(e_{m+1}(\delta_m)) = \delta_m^{\alpha+x(m)}$:

$$\begin{aligned} i^{P_{m+1}}(e_{m+1}(\delta_m)) &= i_{\alpha,\infty}^{P_{m+1}}(i_{0,\alpha}^{P_{m+1}}(e_{m+1}(\delta_m))) = i_{\alpha,\infty}^{P_{m+1}}(j_{i_{0,\alpha}^{P_m}(E_m)}^{P'_m}(e_m(\delta_m))) = \\ &= i_{\alpha,\infty}^{P_{m+1}}(j_{i_{0,\alpha}^{P_m}(E_m)}^{P_m}(e_m(\delta_m))) = i_{\alpha,\infty}^{P_{m+1}}(\delta_m^{\alpha+x(m)}) = \delta_m^{\alpha+x(m)}. \end{aligned}$$

Finally consider the case where either $m \in d \setminus d'$ or $m \in d'$ but $u(m) = 0$. Let ℓ be the restriction to N_m of the ultrapower embedding of $N_{m,\alpha+x(m)}$ by $D_m^{\alpha+x(m)}$. Note that the bottom part of the diagram in Figure 4 is identical to the bottom part of the diagram in Figure 3 and in particular it commutes. In fact the whole diagram commutes and the key to that is that the embedding ℓ is the restriction to N_m of $j_{D^*}^{N_m[G_m]}$ where D^* is the $N_m[G_m]$ -ultrafilter generated by $D_m^{\alpha+x(m)}$. The justification for this is as in Equation 5. The commutativity of the rest of the diagram is a straightforward verification, and the remainder of the proof of the claim in this case is then identical to the previous part.

This completes the proof, but let us note here that in the case where $m \in d'$ we obtain

$$N_{m+1} = j_{\overline{W}_{m+1}}(V) = j_{\overline{W}_m}(V) = N_m.$$

This is because in this case $N_{m+1,\alpha} = N_{m,\alpha+x(m)+1}$. Moreover,

$$(6) \quad V[G]_{\overline{W}_{m+1}} = N_{m+1}[G \times G_{m+1}] = N_m[G \times G_m] = V[G]_{\overline{W}_m}$$

Indeed G_m and G_{m+1} differ by exactly one ordinal since they are given the sequences of sets of indiscernibles associated with essentially the same complete iterations (see also Proposition 3.5). \square

$$\begin{array}{ccccc}
V[G]_{\overline{W}_m} & \xrightarrow{D_m^{u,x}} & V[G]_{\overline{W}_{m+1}} & & \\
\cup & & \cup & & \\
N_m[G_m] & \xrightarrow{D^*} & N_{m+1}[G_{m+1}] & & \\
\cup & & \cup & & \\
N_m & \xrightarrow{\ell} & N_{m+1} & & \\
\uparrow i_{\alpha+x(m),\infty}^{P_m} & & \uparrow i_{\alpha,\infty}^{P_{m+1}} & & \\
N_{m,\alpha+x(m)} & \xrightarrow{D_m^{\alpha+x(m)}} & N_{m+1,\alpha} & & \\
\uparrow i_{0,\alpha}^{P_m}(E_m) & & \uparrow i_{0,\alpha}^{P_m}(E_m) & & \nwarrow i_{0,\alpha}^{P_{m+1}} \\
N_{m,\alpha} & \xrightarrow{D_m^\alpha} & N'_{m,\alpha} & & \\
\uparrow i_{0,\alpha}^{P_m} & & \uparrow i_{0,\alpha}^{P'_m} & & \\
P_m & \xrightarrow{D_m^0} & P'_m & \xrightarrow{E_m} & P_{m+1} \\
\uparrow e_m & & \uparrow e_m & \nearrow e_{m+1} & \\
V_{W_m} & \xrightarrow{D_m} & V_{W_{m+1}} & &
\end{array}$$

FIGURE 4. The case where $u(m) \neq 1$

Lemma 5.6. *Fix an internal iteration (D_0, \dots, D_{n-1}) of normal ultrafilters, let d and d' be as in the paragraph following Theorem 5.3. Suppose that $d = d'$ and fix $u : d \rightarrow \{0, 1\}$ and $x : d \rightarrow \omega$. Let $\overline{W} = \sum(D_0, \dots, D_{n-1})_x^u$. Then in $V[G]$ there is an internal iteration $(F_0, \dots, F_{\ell-1})$ of normal ultrafilters such that $V[G]_{\overline{W}} = V[G]_{F_0, \dots, F_{\ell-1}}$.*

Proof. An easy induction using the definition of $\sum(D_0, \dots, D_{n-1})_x^u$ in the case $d = d'$. Note that in the case that $m \notin d$, $D_m^{u,x}$ is an internal normal ultrafilter of $V[G]_{\overline{W}_m}$. If $m \in d$ then $m \in d'$ by our assumption and $V[G]_{\overline{W}_m} = V[G]_{\overline{W}_{m+1}}$ which follows by Equation 6 if $u(m) = 0$ or since $D_m^{u,x}$ is principal in the case that $u(m) = 1$. \square

5.2. Classifying the extensions of sums of normals. In this section, we classify the extensions to $V[G]$ of sums of normal ultrafilters; i.e., ultrafilters of the form $\Sigma(D_0, \dots, D_n)$. As expected, the proof is by induction on n . Recall that given a finite iteration (D_0, \dots, D_n) , we define $d = d(D_0, \dots, D_n)$ as the set of all $m \leq n$ such that $\delta_m \in j_{0,m}(\Delta)$ and $d' = d'(D_0, \dots, D_n)$ as the set of $m \in d$ such that $D_m = j_{0,m}(\vec{U})_{\delta_m}$.

Theorem 5.7. *Let \overline{W} be a countably complete $V[G]$ -ultrafilter extending $\Sigma(D_0, \dots, D_n)$. Then $\overline{W} = \Sigma(D_0, \dots, D_n)_x^u$ for some $u : d' \rightarrow \{0, 1\}$ and $x : d \rightarrow \omega$.*

Proof. We follow a similar argument to the one in Theorem 4.5. Suppose inductively that we have classified the extensions of $W_m = \Sigma(D_0, \dots, D_{m-1})$ and let us classify the extensions of $W_{m+1} = \Sigma(D_0, \dots, D_m)$. Let \overline{W}_{m+1} be an ultrafilter on κ^{m+1} extending W_{m+1} to a $V[G]$ -ultrafilter. Note that $[id]_{\overline{W}_{m+1}} = (\bar{\delta}_0, \dots, \bar{\delta}_m)$ for some increasing sequence of ordinals. Therefore there is a factor map $k : V_{W_{m+1}} \rightarrow j_{\overline{W}_{m+1}}(V)$ such that $j_{\overline{W}_{m+1}} \upharpoonright V = k \circ j_{W_{m+1}}$ and $k([id]_{W_{m+1}}) = [id]_{\overline{W}_{m+1}}$.

Since \overline{W}_{m+1} extends W_{m+1} , $\pi_*(\overline{W}_{m+1})$ extends W_m where $\pi : \kappa^{m+1} \rightarrow \kappa^m$ denotes the projection to the first m -coordinates. By the induction hypothesis, it follows that $\pi_*(\overline{W}_{m+1})$ must be equal to $\overline{W}_m = \Sigma(D_0, \dots, D_{m-1})_{x'}^{u'}$ for some u', x' . Therefore there is an elementary embedding $\ell : V[G]_{\overline{W}_m} \rightarrow V[G]_{\overline{W}_{m+1}}$ such that $\ell \circ j_{\overline{W}_m} = j_{\overline{W}_{m+1}}$ and $\ell([id]_{\overline{W}_m}) = (\bar{\delta}_0, \dots, \bar{\delta}_{m-1})$.

Let η be the least ordinal such that $\ell(\eta) > \bar{\delta}_m$ and let \overline{U} denote the $V[G]_{\overline{W}_m}$ -ultrafilter on η derived from ℓ using $\bar{\delta}_m$. By Corollary 2.3, $\ell = j_{\overline{U}}$ and $[id]_{\overline{U}} = \bar{\delta}_m$. Let e_m, i^{P_m}, N_m be defined as before (after Theorem 5.3) for $\overline{W}_m = \Sigma(D_0, \dots, D_{m-1})_{x'}^{u'}$, and denote by $i_\alpha = i_{0,\alpha}^{P_m} \circ e_m : V_{W_n} \rightarrow N_m$ and let $i = i_{0,\infty} = i^{P_m} \circ e_m$. Let $\tilde{U} = \overline{U} \cap N_m$, then there is a factor map $k_{\tilde{U}} : (N_m)_{\tilde{U}} \rightarrow j_{\overline{W}_{m+1}}(V)$ such that $j_{\overline{U}} \upharpoonright N_m = k_{\tilde{U}} \circ j_{\tilde{U}}$ and $k_{\tilde{U}}([id]_{\tilde{U}}) = \bar{\delta}_m$. Then the following diagram commutes:

$$\begin{array}{ccccc}
 V[G] & \xrightarrow{j_{\overline{W}_m}} & V[G]_{\overline{W}_m} & \xrightarrow{j_{\overline{U}}} & V[G]_{\overline{W}_{m+1}} \\
 & & \cup & & \cup \\
 & & N_m & \xrightarrow{j_{\tilde{U}}} & (N_m)_{\overline{U}} \xrightarrow{k_{\tilde{U}}} j_{\overline{W}_{m+1}}(V) \\
 \cup & & \nearrow i & & \nearrow k \\
 V & \xrightarrow{j_{W_m}} & V_{W_m} & \xrightarrow{j_{D_m}} & V_{W_{m+1}}
 \end{array}$$

FIGURE 5. The decomposition of $j_{\overline{W}_{m+1}}$.

We claim that $i[D_m] \subseteq \tilde{U}$. To see this, let $X \in D_m$, then

$$\begin{aligned}
 [id]_{D_m} \in j_{D_m}(X) &\Rightarrow \bar{\delta}_m \in k(j_{D_m}(X)) \\
 &\Rightarrow k_{\tilde{U}}([id]_{\tilde{U}}) \in k_{\tilde{U}}(j_{\tilde{U}}(i(X))) \\
 &\Rightarrow [id]_{\tilde{U}} \in j_{\tilde{U}}(i(X)) \Rightarrow i(X) \in \tilde{U}
 \end{aligned}$$

Next we will prove that \tilde{U} is equal to one of the following ultrafilters:

- $i(D_m)$.

- $p_{\delta_m^{\alpha+n}}$ for some $n < \omega$.
- $D_m^{\alpha+n}$ for some $n < \omega$.

Once we prove the above, it will follow that \tilde{U} is the ultrafilter that was denoted by \tilde{D}_m which by the previous part generates the ultrafilter $D_m^{u,x}$ in $V[G]_{\overline{W}_m}$. Hence $\overline{U} = D_m^{u,x}$ for an appropriate extension of u', x' to u, x determined by the value of \tilde{U} . This will end the proof as by definition,

$$\overline{W}_{m+1} = \Sigma(\overline{W}_m, \overline{U}) = \Sigma(\overline{W}_m, D_m^{u,x}) = \Sigma(D_0, \dots, D_m)_x^u$$

Let α be the first stage of the iteration such that the critical point of $i_{\alpha, \infty}^{P_m}$ is at least $i_\alpha(\delta_m)$. We will show that $i_{\alpha, \infty}^{P_m}[i_\alpha(D_m)] \subseteq \tilde{U}$. Note that every generator of i_α is less than $i_\alpha(\delta_m)$; this follows from our choice of α and the fact that e_m is an iteration of ultrafilters on cardinals below δ_m . Similarly, i_α is continuous at δ_m and therefore $i_\alpha[D_m]$ generates $i_\alpha[D_m] \cup F$, where F is the tail filter on $i_\alpha(\delta_m)$. Applying Lemma 3.12 we conclude that $i_\alpha[D_m]$ generates $i_\alpha(D_m)$. Since $i[D_m] \subseteq \tilde{U}$ it follows that $i_{\alpha, \infty}^{P_m}[i_\alpha(D_m)] \subseteq \tilde{U}$.

We first consider the case where $m \notin d$, meaning $\delta_m \notin j_{0,m}(\Delta)$. Hence $\text{crit}(i_{\alpha, \infty}^{P_m}) > i_\alpha(\delta_m)$. It follows that $\tilde{U} = i_\alpha(D_m) = i(D_m)$.

Now suppose that $m \in d$, namely $\delta_m \in j_{0,m}(\Delta)$. The analysis of \tilde{U} is an application of Lemma 3.15 in the case $M = N_\alpha^m$, $i = i_{\alpha, \infty}^{P_m}$ and the ultrafilter $i_\alpha(D_m)$ which is a normal ultrafilter on $i_\alpha(\delta_m)$, the minimal ordinal in the remaining part of the complete iteration $i_{\alpha, \infty}^{P_m}$ as computed in $N_{m, \alpha}$. We conclude that either \tilde{U} has the desired form or else $\tilde{U} = i_{\alpha+\omega}(D_m)$. But the latter cannot occur, because \tilde{U} extends to a countably complete $V[G]_{\overline{W}_m}$ -ultrafilter (namely, \overline{U}), whereas $i_{\alpha+\omega}(D_m)$ does not since $i_{\alpha+\omega}(\delta_m)$ has countable cofinality in $V[G]_{\overline{W}_m}$. $\square_{\text{Theorem 5.7}}$

6. APPLICATIONS

Our first application resolves the problem of whether Weak UA is equivalent to UA (see [6, Question 9.2.4]).

Lemma 6.1. *Assume that the Mitchell order is linear on normal ultrafilters, and that for every σ -complete ultrafilter U there is an internal iteration of normal ultrafilters (D_0, \dots, D_{n-1}) such that $V_U = V_{D_0, \dots, D_{n-1}}$. Then Weak UA holds.*

Proof. Granting the linearity of the Mitchell order on normal measures, [6, Prop. 2.3.13] states that the Ultrapower Axiom for normal ultrafilters holds. It is then not hard to show that the Ultrapower Axiom holds for internal (finite) iterations of normal ultrafilters (see for example the proof [6, Prop. 8.3.43]). By the second assumption of the lemma, this suffices to compare (without commutativity) every two ultrapowers of σ -complete ultrafilters. \square

Lemma 6.2. *Suppose that the Mitchell order is linear in V and that each normal ultrafilter of $V[G]$ is generated by an ultrafilter of V . Then the Mitchell order is linear in $V[G]$.*

Proof. Let $U, W \in V[G]$ be distinct normal measures on a cardinal κ . Let $U_0 = U \cap V$ and $W_0 = W \cap V$. Then $U_0, W_0 \in V$ generate U, W respectively and therefore they are distinct normal measures in V . Suppose without loss of generality that $U_0 \triangleleft W_0$, and let $k : M_{W_0}^V \rightarrow j_W(V)$ be the factor map. The critical point of k is greater than κ (since both W_0 and W are normal). It follows that $U_0 \subseteq k(U_0) \in j_W(V) \subseteq M_W$. Since $V[G]$ and M_W have the same subsets of κ , $k(U_0)$ also must generate $U \in M_W$. \square

Corollary 6.3 (UA). *Assume GCH and that κ is the least measurable limit of measurables. Let \vec{U} be the sequence of normal measures on all the measurables below κ . Let G be V -generic for \mathbb{P}_κ . Then $V[G] \models \text{weak UA} + \neg \text{UA}$.*

Proof. By [6, 2.3.1], in V the Mitchell order is linear and since every normal ultrafilter in $V[G]$ is generated by a ground model normal measure, the previous lemma can be used to infer that the Mitchell order is linear in $V[G]$. Therefore by Lemma 6.1, it remains to prove that every ultrapower by a σ -complete ultrafilter in $V[G]$ is equal to an ultrapower by a sum of normals. Let $U \in V[G]$ be a σ -complete ultrafilter. Since κ is the least measurable in $V[G]$, U is κ -complete there. By [5], $U_0 = U \cap V$ is a κ -complete ultrafilter on κ in V , and by Theorem 5.3, Lemma 5.6, and Theorem 5.7, we obtain $V[G]_U = V[G]_W$ where W is the sum of a finite iteration of normal ultrafilters.

To see that UA fails in $V[G]$, note that in $V[G]$, by Theorem 4.4, there is an ultrapower M of the universe that admits a nontrivial elementary embedding $k : M \rightarrow M$. This would be impossible if UA held in $V[G]$. The reason is that assuming UA, by [7, Thm. 5.2] there is at most one elementary embedding $j : V[G] \rightarrow M$. Therefore $k \circ j = j$, and so by a standard lemma on the Rudin–Keisler order (proved for example in [7, Cor. 4.29]), k would be the identity. \square

We note that the GCH assumption can be replaced by an argument using UA to show that no new V -measures appear in the extension.

Our final application is to a natural question. Can two countably complete uniform ultrafilters on distinct cardinals have the same ultrapower? That is, given such ultrafilters U_0, U_1 , can V_{U_0} be equal to V_{U_1} ? One obstruction is the following:

Proposition 6.4. *Suppose that U_0 and U_1 are countably complete uniform ultrafilters on regular cardinals κ_0 and κ_1 , and assume $V_{U_0} = V_{U_1}$. Then $\kappa_0 = \kappa_1$.*

Proof. Since j_{U_0} and j_{U_1} are elementary embeddings from V into the same inner model, we can appeal to a theorem of Woodin [7, Theorem 3.4] to obtain that $j_{U_0} \restriction \text{Ord} = j_{U_1} \restriction \text{Ord}$. Assume without loss of generality

that $\kappa_0 \leq \kappa_1$. Then since U_1 is uniform on κ_1 , j_{U_1} is discontinuous at κ_1 . It follows that j_{U_0} is discontinuous at κ_1 . Since κ_1 is regular and j_{U_0} is discontinuous at κ_1 , we cannot have $\kappa_0 < \kappa_1$ by [6, Lemma 2.2.34]. Therefore $\kappa_0 = \kappa_1$. \square

The following example shows that the assumption above that κ_0 and κ_1 are regular cardinals is necessary. It also demonstrates one of the complications arising in the attempt to extend our results on extensions of κ -complete ultrafilters on κ to arbitrary countably complete ultrafilters.

For the remainder of the paper, let λ be a measurable cardinal and let $\kappa > \lambda$ denote the least limit of measurable cardinals of cofinality λ . Let Δ denote the set of measurable cardinals strictly between λ and κ , and let $\vec{U} : \Delta \rightarrow V$ assign to each such measurable cardinal a normal ultrafilter. Finally, let \mathbb{P}_κ be the discrete Magidor product of Prikry forcings associated with \vec{U} and let $G \subseteq \mathbb{P}_\kappa$ be V -generic.

Lemma 6.5. *If D is a normal ultrafilter on λ , then $j_D^{V[G]} \restriction V = i \circ j_D$ where $i : V_D \rightarrow N$ is the complete iteration of V_D by $j_D^V(\vec{U}) \restriction (\kappa, j_D^V(\kappa))$. Moreover $j_D^{V[G]}(G) = (G \cap V_D) \times G_{\vec{s}}$ where \vec{s} is the sequence of sets of indiscernibles associated with the complete iteration of $j_D^V(\vec{U}) \restriction (\kappa, j_D^V(\kappa))$.*

Proof. Note that $G \cap V_D$ is V_D -generic on $\mathbb{P}_\kappa(j_D(\vec{U}) \restriction \kappa)$, and therefore by the Mathias criterion and Lemma 3.4,

$$H = (G \cap V_D) \times G_{\vec{s}}$$

is N -generic on $i \circ j_D(\mathbb{P}_\kappa)$. Moreover, if $p \in G$, then $j_D^V(p) \restriction \kappa \in G \cap V_D$ and $j_D^V(p) \restriction (\kappa, j_D^V(\kappa))$ is a pure condition, and so $i(j_D^V(p)) \in (G \cap V_D) \times G_{\vec{s}}$. It follows that $i \circ j_D : V \rightarrow N$ lifts to an elementary embedding $j : V[G] \rightarrow N[H]$ with $j(G) = H$.

To show that $j = j_D^{V[G]}$ it suffices by Corollary 2.3 to show that $N[H] = \text{Hull}^{N[H]}(j[V[G]] \cup \{\lambda\})$. Since $i[V_D] = \text{Hull}^N(j[V] \cup \{\lambda\})$, we have

$$i[V_D] \cup \{G_{\vec{s}}\} \subseteq \text{Hull}^{N[H]}(j[V[G]] \cup \{\lambda\})$$

and $N[G_{\vec{s}}] \subseteq \text{Hull}^{N[H]}(j[V[G]] \cup \{\lambda\})$ by Lemma 3.4 applied in V_D . Since $N[H] = N[G_{\vec{s}}][G \cap V_D]$ and $N[G_{\vec{s}}] \cup \{G \cap V_D\} \subseteq \text{Hull}^{N[H]}(j[V[G]] \cup \{\lambda\})$, it follows that $N[H] = \text{Hull}^{N[H]}(j[V[G]] \cup \{\lambda\})$, as desired. \square

Proposition 6.6. *In $V[G]$, there are countably complete uniform ultrafilters on λ and κ with the same ultrapower.*

Proof. Let D be a normal ultrafilter on λ . Let $f : \lambda \rightarrow V_\kappa$ be the increasing enumeration of \vec{U} , and let $U = [f]_D$. Then in V_D , U is a normal ultrafilter on the least measurable $\gamma > \kappa$. Finally, let $W = \Sigma(D, U)$. Then W is a uniform λ -complete ultrafilter on κ^2 .

We claim that there is an extension W^* of W to a uniform λ -complete $V[G]$ -ultrafilter on κ^2 such that $V[G]_{W^*} = V[G]_D$.

We will define W^* as the analog of the canonical lift of W (defined in Section 3.1) to this situation. The restricted ultrapower of W^* will be the elementary embedding $i \circ j_W^V$ where $i : V_W \rightarrow N$ is the complete iteration of V_W by $j_W(\vec{U}) \restriction (\kappa, j_W(\kappa))$. The image generic will be $(G \cap V_W) \times G_{\vec{t}}$ where \vec{t} is the sequence of sets of indiscernibles associated with the complete iteration of $j_W(\vec{U})$. The seed will just be $i([id]_W)$. These three ingredients uniquely determine W^* , and it is not hard to verify that a $V[G]$ -ultrafilter $W^* \supseteq W$ with these invariants exists.

Note that the complete iteration of V_W by $j_W(\vec{U}) \restriction (\kappa, j_W(\kappa))$ is just the tail of the complete iteration of V_D by $j_D(\vec{U}) \restriction (\kappa, j_D(\kappa))$ after applying the first measure. Therefore by Lemma 6.5, $V[G]_{W^*} = N[(G \cap N) \times G_{\vec{t}}] = V[G]_D$, noting that the sequence \vec{t} differs from the sequence \vec{s} of sets of indiscernibles associated with $j_D(\vec{U}) \restriction (\kappa, j_D(\kappa))$ by just one ordinal.

It remains to show that W^* is a uniform ultrafilter on κ^2 . The reason is that $j_{W^*} \restriction V[G]_\kappa = j_D^{V[G]} \restriction V[G]_\kappa$, while $j_{W^*} \neq j_D^{V[G]}$, the latter following from the fact that

$$j_D^{V[G]}(G) = G \times G_{\vec{s}} \neq G \times G_{\vec{t}} = j_{W^*}(G)$$

If W^* were not uniform on κ^2 , then W^* would be Rudin–Keisler equivalent to an ultrafilter Z on some $\gamma < \kappa$ derived from j_{W^*} and some $\xi < j_{W^*}(\gamma)$. But then Z is also derived from j_D and ξ , so $W^* \leq_{RK} Z \leq_{RK} D$. Since D is normal and W^* is nonprincipal, it follows that D and W^* are Rudin–Keisler equivalent, contrary to the fact that $j_{W^*} \neq j_D^{V[G]}$. \square

7. PROBLEMS

We list out a few related problems we did not address:

Question 7.1. Can we characterize all the σ -complete extensions of a σ -complete ultrafilter on V after the discrete Magidor product? In particular, are there only countably many extensions?

Question 7.2. Can we characterize the σ -complete extensions of sums of normals after other types of iterations of Prikry forcing?

Question 7.3. Working over any ground model V , can we find a characterization of all the extensions of a countably complete ultrafilter to a countably complete ultrafilter after the discrete Magidor product?

We conjecture that if κ is strongly compact then after a discrete Magidor product below κ , there is a κ -complete V -ultrafilter over κ which has uncountably many lifts.

Question 7.4. Is there a forcing that preserves UA and adds a subset X to the least supercompact cardinal κ such that $X \notin V[Y]$ for any $Y \subseteq V$ of cardinality less than κ ?

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