

# A FRAMEWORK FOR FORCING CONSTRUCTIONS AT SUCCESSORS OF SINGULAR CARDINALS

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ABSTRACT. We describe a framework for proving consistency results about singular cardinals of arbitrary cofinality and their successors. This framework allows the construction of models in which the Singular Cardinals Hypothesis fails at a singular cardinal  $\kappa$  of uncountable cofinality, while  $\kappa^+$  enjoys various combinatorial properties.

As a sample application, we prove the consistency (relative to that of ZFC plus a supercompact cardinal) of there being a strong limit singular cardinal  $\kappa$  of uncountable cofinality where SCH fails and such that there is a collection of size less than  $2^{\kappa^+}$  of graphs on  $\kappa^+$  such that any graph on  $\kappa^+$  embeds into one of the graphs in the collection.

## INTRODUCTION

The class of uncountable regular cardinals is naturally divided into three disjoint classes: the successors of regular cardinals, the successors of singular cardinals and the weakly inaccessible cardinals. When we

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consider a combinatorial question about uncountable regular cardinals, typically these classes require separate treatment and very frequently the successors of singular cardinals present the hardest problems. In particular there are subtle constraints (for example in cardinal arithmetic) on the combinatorics of successors of singular cardinals, and consistency results in this area often involve large cardinals.

To give some context for our work, we review a standard strategy for proving consistency results about the successors of regular cardinals. This strategy involves iterating  $<\kappa$ -closed  $\kappa^+$ -cc forcing with  $<\kappa$ -supports for some regular cardinal  $\kappa$ , with the plan that the whole iteration will also enjoy the  $\kappa^+$ -chain condition. The  $\kappa^+$ -chain condition of the iteration will of course ensure that all cardinals are preserved, and is also very helpful in the “catch your tail” arguments which frequently appear in iterated forcing constructions.

When  $\kappa = \omega$  this proof strategy is completely straightforward as any finite support iteration of ccc forcing is ccc; for regular  $\kappa > \omega$  we need to assume that  $\kappa^{<\kappa} = \kappa$  and that the iterands have some strong form of  $\kappa^+$ -cc and some other properties in order to ensure  $\kappa^+$ -cc for the iteration (this issue is extensively discussed in §1 below). When  $\kappa$  is singular the strategy is no longer available, and this is one difficulty among many in proving consistency results involving singular cardinals and their successors.

Džamonja and Shelah [5] introduced a new idea, which we briefly describe. Initially  $\kappa$  is a supercompact cardinal whose supercompactness is indestructible under  $<\kappa$ -directed closed forcing. The final model is obtained by a two-step forcing. The first step,  $\mathbb{P}$ , is a  $<\kappa$ -directed closed and  $\kappa^+$ -cc iteration, whilst the second step is Prikry forcing,  $Pr_U$ , defined from a normal measure  $U$  on  $\kappa$  in  $V[G]$ , where  $G$  is a  $\mathbb{P}$ -generic filter over  $V$ . The iteration  $\mathbb{P}$  is designed to anticipate and deal with  $Pr_U$ -names for subsets of  $\kappa^+$ , so that after forcing over  $V[G]$  with  $Pr_U$  we obtain the desired consistency result. Džamonja and Shelah used this method to obtain the consistency, for  $\kappa$  singular strong limit of cofinality  $\omega$ , of the existence of a family of fewer than  $2^{\kappa^+}$  many graphs on  $\kappa^+$  which are jointly universal for all graphs on  $\kappa^+$ .

A well known early interaction between model theory and set theory gives one that if  $2^\kappa = \kappa^+$  there is a saturated graph (*i.e.*, model of the theory of graphs) on  $\kappa^+$  and any such graph is universal. So the point of results such as that of Džamonja and Shelah is to address

the possibility of having small universal families of graphs on  $\kappa^+$  when  $2^\kappa > \kappa^+$ .

In this paper we build a similar framework in which the final forcing step is a version of Radin forcing, and changes the cofinality of  $\kappa$  to become some uncountable cardinal less than  $\kappa$ . After building the framework, we prove a version of the result on universal graphs mentioned in the last paragraph.

The need for large cardinals in the broad context of combinatorics at singular cardinals and their successors is at least partially explained by the theory of core models and covering lemmas. If there is no inner model with a Woodin cardinal then there is an inner model  $K$  with many strong combinatorial properties (for example GCH and square hold), and such that  $\kappa^+ = (\kappa^+)^K$  for every singular cardinal  $\kappa$ . This resemblance between  $V$  and  $K$  in the absence of inner models with large enough cardinals exerts a strong influence on the combinatorics of  $\kappa^+$  in  $V$ , for example it implies that  $\square_\kappa$  holds in  $V$  under this hypothesis.

In the instance of the results on universal graphs we obtain a model in which  $\kappa$  is a singular strong limit cardinal where  $2^\kappa > \kappa^+$ , i.e. the singular cardinals hypothesis fails. It is known through work of Gitik, Mitchell and Woodin that the consistency strength of the singular cardinals hypothesis failing alone is exactly that of a measurable cardinal  $\kappa$  of Mitchell order  $o(\kappa) = \kappa^{++}$ . Thus some large cardinal hypotheses are necessary for these results on universal graphs that we prove.

This paper is in some sense a sequel to the work by Džamonja and Shelah [5], and so we briefly record some of the innovations introduced here.

- Prikry forcing at  $\kappa$  is homogeneous and adds no bounded subsets of  $\kappa$ , while Radin forcing has neither of these features. This entails major changes in the analysis of names for  $\kappa^+$  in the final model, the proof of  $\kappa^+$ -cc for the main iteration, and the proof that the final model has a small jointly universal family.
- The arguments of [5] involve a complex iteration scheme which is used to build a Prikry forcing  $Pr_U$ , and would have become even more complex if we had used it to build a suitable Radin forcing. In this paper we use diamond sequences to achieve similar goals.
- One of the central points is that our main iteration enjoys a strong form of the  $\kappa^+$ -chain condition. None of the standard

preservation theorems were quite suitable to show this, so we took a detour into iteration theory to formulate and prove a suitable preservation theorem.

The paper is organized as follows: §1 shows that cardinals are preserved in  $<\kappa$ -support iterations of certain types of  $<\kappa$ -closed, stationary  $\kappa^+$ -chain condition forcings (and as a spin-off we give a generalized Martin's axiom for these forcings). §2 is on preservation of diamond through forcing iterations. §3 collects relevant material on Radin forcing. §4 describes the long Prikry/Mathias forcing and its variant for adding Radin names for universal graphs. §5 contains the proof of the stationary  $\kappa^+$ -chain condition for the forcings of §4. §6 gives the main iteration. §7 gets a small family of universal graphs at a cardinal of uncountable singular cofinality.

The problem of the existence of a small family of universal graphs has some independent interest, and is also a natural test question for our forcing framework. In a projected sequel to this paper we will consider other applications.

**Notation.** Card and On are the classes of cardinals and ordinals respectively. The size of a set  $A$  is denoted by either  $\overline{A}$  or  $|A|$ . If  $X$  is a set and  $\kappa$  is a cardinal then  $\mathcal{P}(X)$  is the set of all subsets of  $X$  and  $[X]^\kappa$  is the set of all subsets of  $X$  of size  $\kappa$ . We define  $[X]^{<\kappa}$ , etc., in the obvious way. If  $X, Y$  are sets then  ${}^XY$  is the set of functions from  $X$  to  $Y$ .

We designate names for the projection functions on cartesian products. If  $X, Y$  are sets we define  $\pi_0 : X \times Y \longrightarrow X$  and  $\pi_1 : X \times Y \longrightarrow Y$  by, if  $x \in X$  and  $y \in Y$  then  $\pi_0(x, y) = x$  and  $\pi_1(x, y) = y$ .

We write  $f \cdot g$  for the composition of the functions  $f$  and  $g$ . When  $f$  and  $g$  agree on  $\text{dom}(f) \cap \text{dom}(g)$  we write  $f + g$  for the unique function  $h$  such that  $\text{dom}(h) = \text{dom}(f) \cup \text{dom}(g)$ ,  $h \upharpoonright \text{dom}(f) = f$  and  $h \upharpoonright \text{dom}(g) = g$ .

If  $X$  is a set of ordinals we write  $\text{ssup}(X)$  for the *strong supremum* of  $X$ , that is the least ordinal  $\alpha$  such that  $X \subseteq \alpha$ , and  $\text{cl}(X)$  for the closure of  $X$  in the order topology.

One *non-standard* piece of notation which will be useful and which we define here is the following. If  $y = \langle y_\tau \mid \tau < \text{lh}(y) \rangle$  is a sequence of sets and  $y_0 \in \text{Card}$  we often write  $\kappa_y$  for  $y_0$ , the first entry in  $y$ .

If  $\mu, \kappa$  are regular cardinals with  $\mu < \kappa$  we write, on occasion,  $S_\mu^\kappa$  for  $\{\xi < \kappa \mid \text{cf}(\xi) = \mu\}$ , and similarly for  $S_{<\mu}^\kappa, S_{\geq\mu}^\kappa$  and so on. If  $S$  is a stationary subset of  $\kappa$  we say that  $T \subseteq S$  is a *club relative to  $S$*  if there is some club  $C \subseteq \kappa$  such that  $T = S \cap C$ .

A function  $g : \kappa \rightarrow \kappa$  is *regressive* on a set  $S \subseteq \kappa$  if for every  $\varepsilon \in S$  we have  $g(\varepsilon) < \varepsilon$ .

A subset  $X$  of a partial order  $(\mathbb{P}, \leq)$  is *linearly ordered* if for all  $p, q \in X$  either  $p \leq q$  or  $q \leq p$ , *directed* if every finite subset of  $X$  has a lower bound in  $X$ , and *centred* if every finite subset of  $X$  has a lower bound in  $\mathbb{P}$ . A partial order  $(\mathbb{P}, \leq)$  is  *$<\kappa$ -closed* if every linearly ordered subset of size  $<\kappa$  of  $\mathbb{P}$  has a lower bound,  *$<\kappa$ -directed closed* if every directed subset of size  $<\kappa$  of  $\mathbb{P}$  has a lower bound, and  *$<\kappa$ -compact* if every centred subset of size  $<\kappa$  of  $\mathbb{P}$  has a lower bound.  $\mathbb{P}$  is *countably compact* if and only if it is  $<\omega_1$ -compact. Clearly any  $<\kappa$ -compact partial order is  $<\kappa$ -directed closed, and any  $<\kappa$ -directed closed partial order is  $<\kappa$ -closed.

If  $(\mathbb{P}, \leq)$  is a partial order and  $q, r \in \mathbb{P}$  we write  $q \parallel r$  to mean that  $q$  and  $r$  are compatible in  $\mathbb{P}$ , that is there is some  $p \in \mathbb{P}$  such that  $p \leq q, r$ . If  $(\mathbb{Q}, \leq)$  is a sub-partial order of  $(\mathbb{P}, \leq)$  and  $q, r \in \mathbb{Q}$  we write  $q \parallel_{\mathbb{Q}} r$  to mean  $q$  and  $r$  are compatible in  $\mathbb{Q}$ , that there is some  $p \in \mathbb{Q}$  such that  $p \leq q, r$ . A partial order is *splitting* if every element has two incompatible extensions.

A partial order  $(\mathbb{P}, \leq)$  is *well-met* if every compatible pair of elements has a greatest lower bound: *i.e.*, for all  $p, q \in \mathbb{P}$  if  $p \parallel q$  then there is some  $r \in \mathbb{P}$  such that  $r \leq p, q$  and for all  $s \in \mathbb{P}$  with  $s \leq p, q$  we have  $s \leq r$ .

For a regular cardinal  $\kappa$ , a partial order  $\mathbb{P}$  has the  $\kappa^+$ -*stationary chain condition* if and only if for every sequence  $\langle p_i \mid i < \kappa^+ \rangle$  of conditions in  $\mathbb{P}$  there exist a club set  $C \subseteq \kappa^+$  and a regressive function  $f$  on  $C \cap S_\kappa^{\kappa^+}$  such that for all  $\alpha, \beta \in C \cap S_\kappa^{\kappa^+}$  with  $f(\alpha) = f(\beta)$  the conditions  $p_\alpha$  and  $p_\beta$  are compatible. We note that by an easy application of Fodor's lemma, this property implies that  $\mathbb{P}$  enjoys the strengthened form of the  $\kappa^+$ -Knaster property in which any  $\kappa^+$ -sequence of conditions has a stationary subsequence of pairwise compatible conditions.

When forcing with a partial order  $(\mathbb{P}, \leq)$  over a model  $V$  we take the notions of *names* and *canonical names* to be as in [8] writing  $\dot{x}$  for a  $\mathbb{P}$ -name in  $V$  and  $\hat{y}$  for a standard  $\mathbb{P}$ -name for  $y \in V$ . We will freely use the well-known *Maximum Principle*, which states that if  $\Vdash \exists x \phi(x, \hat{y}, \dot{G})$

then there is a name  $\dot{x}$  such that  $\Vdash \phi(\dot{x}, \dot{y}, \dot{G})$ . Usually our usage should be clear: as is customary we take the Boolean truth values  $\mathbb{0}, \mathbb{1}$  to be identified with the (ordinal) elements of  $\{0, 1\}$ . Thus forcing names for truth values are names for ordinals  $< 2$ . In the context of forcing, if  $p, q \in \mathbb{P}$  then  $p \leq q$  means that  $p$  is stronger than  $q$ .

The Laver iteration  $\mathbb{L}$  for a supercompact cardinal  $\kappa$  is a  $\kappa$ -cc forcing poset of cardinality  $\kappa$  which make the supercompactness of  $\kappa$  indestructible under  $< \kappa$ -directed closed forcing [9].

If  $\mathcal{G} = (X, E)$  and  $\mathcal{H} = (Y, F)$  are graphs then  $f : \mathcal{G} \rightarrow \mathcal{H}$  is an *embedding of  $\mathcal{G}$  into  $\mathcal{H}$  as an induced subgraph* if  $\forall x_0 \in X \forall x_1 \in X (x_0 E x_1 \iff f(x_0) F f(x_1))$ . Since this is the only kind of graph embedding which concerns us we will simply call them *embeddings*.

Let  $\kappa$  be a regular cardinal. We say that a family  $\mathcal{F}$  of graphs on  $\kappa$  is *jointly universal* for graphs of size  $\kappa$  if for every graph  $\mathcal{G} = (\kappa, E)$  there is some  $\mathcal{H} = (\kappa, F) \in \mathcal{F}$  and some embedding  $f : \mathcal{G} \rightarrow \mathcal{H}$  of  $\mathcal{G}$  into  $\mathcal{H}$ . We say that  $\mathcal{F}$  is a *small universal family* if  $\overline{\mathcal{F}} < 2^\kappa$ .

If  $\kappa^+$  is a successor cardinal a  $\kappa^+$ -*tree* is a tree of size  $\kappa^+$ , height  $\kappa^+$  and each level of size at most  $\kappa$ . A *binary  $\kappa^+$ -tree* is a  $\kappa^+$ -tree such that each point in the tree has exactly two successors in the tree order. If  $\Upsilon$  is a cardinal greater than  $\kappa^+$  a  $\kappa^+$ -*Kurepa tree with  $\Upsilon$ -many branches* is a  $\kappa^+$ -tree with  $\Upsilon$ -many branches of length  $\kappa^+$ . If there is such a tree there is one which is binary and a subtree of the complete binary tree  ${}^{<\kappa^+}2$  (see, for example, [8], Chapter (2)). In a slight abuse of terminology, we refer here to binary  $\kappa^+$ -Kurepa subtrees of  ${}^{<\kappa^+}2$  as binary  $\kappa^+$ -Kurepa trees.

The *usual forcing to add a  $\kappa^+$ -Kurepa tree with  $\Upsilon$ -many branches*, due to Solovay(?), is the forcing notion in which conditions are pairs  $(t, f)$  consisting of a binary sub-tree,  $t$ , of  ${}^{<\kappa^+}2$  of successor height, say  $\gamma + 1$ ,  $< \kappa^+$ , each level of size at most  $\kappa$  and each point in the tree having a successor of height  $\gamma$ , and a bijection  $f$  between a subset of  $\Upsilon$  and the set of points of height  $\gamma$ . The ordering is that  $p = (t^p, f^p) \leq q = (t^q, f^q)$  if  $t^q$  is obtained by, in Kunen's vivid précis, 'sawing off  $t^p$  parallel to the ground,'  $\text{dom}(f^q) \subseteq \text{dom}(f^p)$  and  $f^q(\xi) <^p f^p(\xi)$ , where  $<^p$  is the tree order on  $t^p$ . This forcing has the  $\kappa^{++}$ -chain condition and is  $< \kappa^+$ -directed closed with greatest lower bounds: every directed set of conditions of size at most  $\kappa$  has a greatest lower bound.

## 1. SOME ITERATED FORCING THEORY

In the classical exposition of iterated forcing Baumgartner [1, §4] wrote

The search for extensions of MA for larger cardinals has proved to be rather difficult.

One reason for this is that for  $\kappa$  regular and uncountable, an iteration of  $<\kappa$ -closed and  $\kappa^+$ -cc forcing posets with supports of size less than  $\kappa$  does not in general have the  $\kappa^+$ -cc. For example, a construction due to Mitchell described in a paper of Laver and Shelah [10] shows that in  $L$  there is an iteration of length  $\omega$  of countably closed  $\aleph_2$ -cc forcing posets such that the inverse limit at stage  $\omega$  does not have the  $\aleph_2$ -cc.

The literature contains several preservation theorems for iterations involving strengthened forms of closure and chain condition, along with corresponding forcing axioms. The first results in this direction are in unpublished work by Laver [1, §4]. Baumgartner [1] proved that under CH an iteration with countable supports of countably compact  $\aleph_1$ -linked forcing posets is  $\aleph_2$ -cc, and proved the consistency of some related forcing axioms. Shelah [13] proved that under CH an iteration with countable supports of posets which are countably closed and well-met and which enjoy the stationary  $\aleph_2$ -cc also enjoys the stationary  $\aleph_2$ -cc. Shelah also proved more general results for certain iterations of stationary  $\kappa^+$ -cc posets with supports of size less than  $\kappa$ , and proved the consistency of a number of related forcing axioms.

The main result of this section is a common generalisation of the results of Baumgartner and Shelah quoted above. In order to state the theorem we require a definition.

**Definition 1.1.** Let  $(\mathbb{P}, \leq)$  be a partial order.

- Two descending sequences  $\langle q_i \mid i < \omega \rangle$  and  $\langle r_i \mid i < \omega \rangle$  from  $\mathbb{P}$  are *pointwise compatible* if for each  $i < \omega$  we have  $q_i \parallel r_i$ .
- $(\mathbb{P}, \leq)$  is *countably parallel-closed* if each pair of pointwise compatible descending  $\omega$ -sequences has a common lower bound.

**Theorem 1.2.** *Let  $\kappa$  be an uncountable cardinal with  $\kappa^{<\kappa} = \kappa$ . Every iteration of countably parallel-closed,  $<\kappa$ -closed and stationary  $\kappa^+$ -cc forcing with supports of size less than  $\kappa$  has stationary  $\kappa^+$ -cc.*

*Proof.* Let  $\mathbb{P} = \langle \langle \mathbb{P}_\xi \mid \xi \leq \chi \rangle, \langle \dot{Q}_\xi \mid \xi < \chi \rangle \rangle$  be a  $<\kappa$ -support iteration of forcings such that for each  $\xi < \chi$  it is forced by  $\mathbb{P}_\xi$  that  $\dot{Q}_\xi$  is countably parallel-closed,  $<\kappa$ -closed and stationary  $\kappa^+$ -cc. We prove,

by induction on  $\xi$ , and following the proof of Lemma (1.3) of [13] closely, that for each  $\xi \leq \chi$ ,  $\mathbb{P}_\xi$  has the stationary  $\kappa^+$ -chain condition.

Suppose that  $\mathbb{P}_\varepsilon$  has the stationary  $\kappa^+$ -chain condition for all  $\varepsilon < \xi$ . Let  $\langle p_i \mid i < \kappa^+ \rangle \in {}^{\kappa^+}\mathbb{P}_\xi$ . We construct for each  $i < \kappa^+$  a decreasing  $\omega$ -sequence  $\langle p_i^n \mid n < \omega \rangle$  such that  $p_i^0 = p_i$  and  $p_i^n \in \mathbb{P}_\xi$  for each  $n < \omega$ .

Induction step  $n + 1$ . Suppose we have already defined  $\langle p_i^n \mid i < \kappa^+ \rangle$ . For each  $i < \kappa^+$  and  $\varepsilon < \xi$  we have  $\Vdash_{\mathbb{P}_\varepsilon} "p_i^n(\varepsilon) \in \dot{Q}_\varepsilon"$  and  $p_i^n(\varepsilon) = \mathbb{1}_{\dot{Q}_\varepsilon}$  if  $\varepsilon \notin \text{supp}(p_i^n)$ . As  $\Vdash_{\mathbb{P}_\varepsilon} "\dot{Q}_\varepsilon$  has the stationary  $\kappa^+$ -cc" and  $\langle p_i^n(\varepsilon) \mid i < \kappa^+ \rangle$  names a  $\kappa^+$ -sequence of elements of  $\dot{Q}_\varepsilon$ , we may find  $\mathbb{P}_\varepsilon$ -names  $\dot{C}_\varepsilon^n$  for a club subset of  $\kappa^+$  and  $\dot{g}_\varepsilon^n$  for a regressive function on  $\dot{C}_\varepsilon^n$  witnessing the stationary  $\kappa^+$ -cc for the sequence named by  $\langle p_i^n(\varepsilon) \mid i < \kappa^+ \rangle$ .

As  $\mathbb{P}_\varepsilon$  has the  $\kappa^+$ -chain condition, if  $\Vdash_{\mathbb{P}_\varepsilon} "\dot{D}$  is a club subset of  $\kappa^+"$  there is some club  $D' \in V$  such that  $\Vdash_{\mathbb{P}_\varepsilon} "D' \subseteq \dot{D}"$ . So we may as well assume that  $\dot{C}_\varepsilon^n = \hat{C}_\varepsilon^n$  for some club  $C_\varepsilon^n \in V$ .

For each  $i < \kappa^+$ , dealing with each  $\varepsilon \in \text{supp}(p_i^n)$  inductively and using the  $< \kappa$ -closure of  $\mathbb{P}_\xi$ , find some  $p_i^{n+1} \leq p_i^n$  such that

$$\forall \varepsilon \in \text{supp}(p_i^n) \ p_i^{n+1} \upharpoonright \varepsilon \Vdash_{\mathbb{P}_\varepsilon} " \dot{g}_\varepsilon^n(i) = \rho_\varepsilon^n(i) "$$

for some ordinal  $\rho_\varepsilon^n(i) < i$ . Let  $\rho_\varepsilon^n(i) = 0$  for  $\varepsilon \notin \text{supp}(p_i^n)$ .

Let  $\{\varepsilon_\alpha \mid \alpha < \mu\}$ , for some  $\mu \leq \kappa^+$ , enumerate  $\bigcup \{\text{supp}(p_i^n) \mid n < \omega \ \& \ i < \kappa^+\}$ . For each  $\varepsilon < \xi$  let  $C_\varepsilon = \bigcap_{n < \omega} C_\varepsilon^n$  and let  $C = \{i < \kappa^+ \mid \forall \alpha < i \ (i \in C_{\varepsilon_\alpha})\}$ .

Using the hypothesis that  $\kappa^{< \kappa} = \kappa$ , we can find a club  $E \subseteq C$  and a regressive function  $g$  on  $S_\kappa^{\kappa^+} \cap E$  such that if  $i, i' \in S_\kappa^{\kappa^+} \cap E$ ,  $g(i) = g(i')$  and  $i < i'$  then

- (1)  $\bigcup \{\text{supp}(p_i^n) \mid n < \omega\} \cap \{\varepsilon_\gamma \mid \gamma < i\} = \bigcup \{\text{supp}(p_{i'}^n) \mid n < \omega\} \cap \{\varepsilon_\gamma \mid \gamma < i'\}$
- (2)  $\bigcup \{\text{supp}(p_i^n) \mid n < \omega\} \subseteq \{\varepsilon_\gamma \mid \gamma < i'\}$
- (3) If  $\gamma < i'$ ,  $n < \omega$  and  $\varepsilon_\gamma \in \text{supp}(p_{i'}^n)$  then  $\rho_{\varepsilon_\gamma}^n(i) = \rho_{\varepsilon_\gamma}^n(i')$ .

Note that, by (1), for every  $\gamma$  to which clause (3) applies we have  $\gamma < i$  and  $\varepsilon_\gamma \in \bigcup \{\text{supp}(p_i^n) \mid n < \omega\}$ .

Suppose that  $i < i' < \kappa^+$ ,  $i, i' \in S_\kappa^{\kappa^+} \cap E$  and  $g(i) = g(i')$ . We now construct, by an induction of length  $\xi$ , a condition  $q \in \mathbb{P}_\xi$  which is a common refinement of  $p_i^n$  and  $p_{i'}^n$  for all  $n$ , and hence of  $p_i$  and



$p_{i'}$ . The support of  $q$  will be the union of  $\bigcup\{\text{supp}(p_i^n) \mid n < \omega\}$  and  $\bigcup\{\text{supp}(p_{i'}^n) \mid n < \omega\}$ .

For  $\sigma \in \bigcup\{\text{supp}(p_i^n) \mid n < \omega\} \setminus \bigcup\{\text{supp}(p_{i'}^n) \mid n < \omega\}$ , as  $\Vdash_{\mathbb{P}_\sigma}$  “ $\dot{Q}_\varepsilon$  is countably closed”, take  $q(\sigma)$  to be any  $r$  such that  $q \restriction \sigma \Vdash_{\mathbb{P}_\sigma}$  “ $\forall n < \omega (r \leq p_i^n(\sigma))$ ”. Similarly, for  $\sigma \in \bigcup\{\text{supp}(p_{i'}^n) \mid n < \omega\} \setminus \bigcup\{\text{supp}(p_i^n) \mid n < \omega\}$ , take  $q(\sigma)$  to be any  $r$  such that  $q \restriction \sigma \Vdash_{\mathbb{P}_\sigma}$  “ $\forall n < \omega (r \leq p_{i'}^n(\sigma))$ ”.

Finally, if  $\sigma \in \bigcup\{\text{supp}(p_i^n) \mid n < \omega\} \cap \bigcup\{\text{supp}(p_{i'}^n) \mid n < \omega\}$  then  $\sigma = \varepsilon_\gamma$  for some  $\gamma < i$  (by conditions (1) and (2) above), for each  $n < \omega$  we have  $\rho_{\varepsilon_\gamma}^n(i) = \rho_{\varepsilon_\gamma}^n(i')$  (by (3) above), and  $i, i' \in C_{\varepsilon_\gamma}$  (by the construction of  $C$  and the choice of  $E$ ).

By construction, for each  $n < \omega$  we have  $q \restriction \sigma \Vdash_{\mathbb{P}_\sigma}$  “ $p_i^n(\sigma) \parallel_{\dot{Q}_\sigma} p_{i'}^n(\sigma)$ ”. By the fact that  $\Vdash_{\mathbb{P}_\sigma}$  “ $\dot{Q}_\sigma$  is countably parallel-closed”, we can choose  $q(\sigma)$  to be some  $r$  such that  $q \restriction \sigma \Vdash_{\mathbb{P}_\sigma}$  “ $\forall n < \omega (r \leq p_i^n(\sigma), p_{i'}^n(\sigma))$ ”. Thus for all  $n < \omega$  we have that  $q \restriction (\sigma + 1) \leq p_i^n \restriction (\sigma + 1), p_{i'}^n \restriction (\sigma + 1)$ .

▲1.2

We remark that the previous theorem allows us to give ‘generalised Martin’s axiom’ forcing axioms similar to those formulated by Baumgartner [1] and Shelah [13]. One example is given by the following theorem.

**Theorem 1.3.** *Let  $\kappa$  be an uncountable cardinal such that  $\kappa^{<\kappa} = \kappa$ , and let  $\lambda > \kappa^+$  be a cardinal such that  $\gamma^{<\kappa} < \lambda$  for every  $\gamma < \lambda$ . Then there is a  $<\kappa$ -closed and stationary  $\kappa^+$ -cc forcing poset  $\mathbb{P}$  such that if  $G$  is  $\mathbb{P}$ -generic, then in  $V[G]$  we have  $2^\kappa = \lambda$  and the following forcing axiom holds:*

*For every poset  $\mathbb{Q}$  which is  $<\kappa$ -closed, countably parallel-closed and stationary  $\kappa^+$ -cc, every  $\gamma < \lambda$  and every sequence  $\langle D_i \mid i < \gamma \rangle$  of dense subsets of  $\mathbb{Q}$  there is a filter on  $\mathbb{Q}$  which meets each set  $D_i$ .*

As in [1] and [13], there are variations with weaker hypotheses on  $\lambda$ , yielding weaker forcing axioms which only apply to posets  $\mathbb{Q}$  of bounded size.

The following straightforward lemma indicates some connections between the hypotheses used in [1] and [13], and the ones used here.

**Lemma 1.4.** *Let  $\mathbb{P}$  be a forcing poset.*

- (1) *If  $\mathbb{P}$  is well-met and countably closed then it is countably compact.*

- (2) If  $\mathbb{P}$  is countably compact then it is countably parallel-closed.
- (3) If  $\mathbb{P}$  is  $\kappa$ -linked then it is stationary  $\kappa^+$ -cc.

## 2. PRESERVING DIAMOND UNDER FORCING

In this section we give an account of how versions of the diamond principle at a regular cardinal  $\chi$  are preserved by certain forcing posets. We are most interested in the situation where the forcing poset is an iteration  $\mathbb{P}_\chi$  of length  $\chi$ , and we can find a diamond sequence  $\langle S_\alpha \mid \alpha < \chi \rangle \in V[G_\chi]$  such that  $S_\alpha \in V[G_\alpha]$  for all  $\alpha$ . We will use the results of this section in §6 and §7.

The following result is well-known. For the reader's convenience we will sketch a proof.

**Theorem 2.1.** *Let  $\chi$  be a regular uncountable cardinal, let  $\mathbb{P}$  be a forcing poset of cardinality  $\chi$  which preserves the regularity of  $\chi$  and let  $G$  be  $\mathbb{P}$ -generic over  $V$ .*

- (1) If  $\diamond_\chi$  holds in  $V$  and  $\mathbb{P}$  preserves stationary subsets of  $\chi$  then  $\diamond_\chi$  holds in  $V[G]$ .
- (2) If  $\diamond_\chi^*$  (resp  $\diamond_\chi^+$ ) holds in  $V$  then  $\diamond_\chi^*$  (resp  $\diamond_\chi^+$ ) holds in  $V[G]$ .

*Proof.* (1). Enumerate the elements of  $\mathbb{P}$  as  $p_i$  for  $i < \chi$ , fix in  $V$  a diamond sequence  $\langle T_\alpha \subseteq \alpha \times \alpha \mid \alpha < \chi \rangle$  which guesses subsets of  $\chi \times \chi$ , and in  $V[G]$  define  $S_\alpha = \{\eta < \alpha \mid \exists i < \alpha (p_i \in G \text{ and } (i, \eta) \in T_\alpha)\}$ . Now if  $S = \dot{S}^G \subseteq \chi$  we let  $T = \{(i, \eta) \mid p_i \Vdash \hat{\eta} \in \dot{S}\}$ , and observe that  $\{\alpha \mid T \cap \alpha \times \alpha = T_\alpha\}$  is stationary in  $V$  (hence also in  $V[G]$ ) and  $E = \{\alpha \mid \forall \eta \in S \cap \alpha \exists i < \alpha p_i \in G \text{ and } p_i \Vdash \hat{\eta} \in \dot{S}\}$  is club in  $V[G]$ ; at any point  $\alpha \in E$  such that  $T \cap \alpha \times \alpha = T_\alpha$  we have that  $S \cap \alpha = S_\alpha$ .

(2). The proofs for  $\diamond_\chi^*$  and  $\diamond_\chi^+$  are very similar. The key difference is that the hypothesis that the regularity of  $\chi$  is preserved suffices to see that  $E$  is club in  $V[G]$ , and the stronger form of guessing occurring in the  $\diamond_\chi^*$  and  $\diamond_\chi^+$  gives a club from  $V$  with which to intersect it. ▲<sub>2.1</sub>

**Observation 2.2.** For future reference we note that:

- (1) An entirely similar argument shows that if  $B$  is a stationary subset of  $\chi$  and  $\mathbb{P}$  preserves stationary subsets of  $B$ , then  $\mathbb{P}$  preserves  $\diamond_\chi(B)$ . If  $\mathbb{P}$  preserves the stationarity of  $B$  then  $\mathbb{P}$  preserves  $\diamond_\chi^*(B)$  and  $\diamond_\chi^+(B)$ .

- (2) In both parts of Theorem (2.1), the value of the diamond sequence in  $V[G]$  at  $\alpha$  is computed in a uniform way from  $G \upharpoonright \alpha$  where  $G \upharpoonright \alpha = G \cap \{p_i \mid i < \alpha\}$ . In fact the restriction of the diamond sequence to  $\alpha + 1$  can be computed in a uniform way from  $G \upharpoonright \alpha$ .
- (3) In the proof of part (1) of Theorem (2.1), let  $A$  be the stationary set in  $V[G]$  given by  $A = \{\alpha \mid S \cap \alpha = S_\alpha\}$ . For every  $\alpha \in E$ ,  $S \cap \alpha \in V[G \upharpoonright \alpha]$  and so easily  $E \cap \alpha \in V[G \upharpoonright \alpha]$ . Also, by the preceding remarks,  $A \cap \alpha \in V[G \upharpoonright \alpha]$ . If we now let  $H = A \cap E$  then  $H$  is a stationary set on which  $S$  is guessed correctly and additionally  $H \cap \alpha \in V[G \upharpoonright \alpha]$  for all  $\alpha$  in the closure of  $H$ .

**Proposition 2.3.** *Let  $\kappa, \chi$  be regular cardinals with  $\kappa < \chi$ . Let  $\mathbb{P} = \langle \langle \mathbb{P}_\xi \mid \xi \leq \chi \rangle, \langle \dot{Q}_\xi \mid \xi < \chi \rangle \rangle$  be a forcing iteration with  $< \kappa$ -supports with  $\overline{\mathbb{P}}_\xi < \chi$  for each  $\xi < \chi$ . Let  $G$  be  $\mathbb{P}$ -generic over  $V$ .*

*Suppose  $A$  is a stationary subset of  $S_{\geq \kappa}^\chi$  and  $\diamond_\chi(A)$  holds. Then there is a sequence  $\langle \dot{S}_\xi \mid \xi \in A \rangle$  such that*

- (1) *For all  $\xi \in A$ ,  $\dot{S}_\xi$  is a  $\mathbb{P}_\xi$ -name for a subset of  $\xi$ .*
- (2) *If in  $V[G]$  we define  $S_\xi$  as the interpretation of  $\dot{S}_\xi$  by  $G_\xi$  then the sequence  $\langle S_\xi \mid \xi \in A \rangle$  has the following strengthened form of the  $\diamond_\chi(A)$ -property: for every  $S \subseteq \chi$  there is a stationary set  $H \subseteq A$  such that  $S \cap \xi = S_\xi$  for all  $\xi \in H$ , and in addition  $H \cap \xi \in V[G_\xi]$  for all  $\xi$  in the closure of  $H$ .*

*Proof.* We start by observing that by arguments as in Baumgartner's survey paper on iterated forcing [1, §2] the poset  $\mathbb{P}$  is  $\chi$ -cc. We sketch the proof briefly: given a sequence  $\langle p_i \mid i < \chi \rangle$  of elements of  $\mathbb{P}$  we apply Fodor's theorem and the bound on the size of initial segments to find a stationary set  $U \subseteq S_\kappa^\chi$  and an ordinal  $\eta < \chi$  such that  $\text{supp}(p_i) \cap i \subseteq \eta$  and  $p_i \upharpoonright \eta$  is constant for  $i \in U$ , then find  $i, j \in U$  such that  $\text{supp}(p_i) \subseteq j$  and argue that  $p_i$  is compatible with  $p_j$ .

Noting that  $|\mathbb{P}| = \chi$ , we enumerate  $\mathbb{P}$  as  $\langle p_\xi \mid \xi < \chi \rangle$  and let  $F$  be  $\{\xi < \chi \mid \mathbb{P}_\xi = \{p_\varepsilon \mid \varepsilon < \xi\}\}$ . Since  $\mathbb{P}$  is an iteration with  $< \kappa$ -support,  $F$  is club relative to  $S_{\geq \kappa}^\chi$  and hence  $A \setminus F$  is non-stationary.

Since  $\mathbb{P}$  is  $\chi$ -cc it preserves stationary subsets of  $\chi$ , and we may therefore appeal to Theorem (2.1) and Observation (2.2) to obtain a sequence  $\langle \dot{S}_\xi \mid \xi \in A \cap F \rangle$  such that

- (1) For all  $\xi \in A \cap F$ ,  $\dot{S}_\xi$  is a  $\mathbb{P}_\xi$ -name for a subset of  $\xi$ .

- (2) If in  $V[G]$  we define  $S_\xi$  as the realisation of  $\dot{S}_\xi$  by  $G_\xi$ , then for every  $S \subseteq \kappa$  there is a stationary set  $H \subseteq A \cap F$  such that  $S \cap \xi = S_\xi$  for all  $\xi \in H$  and additionally  $H \cap \xi \in V[G_\xi]$  for all  $\xi$  in the closure of  $H$ .

To finish the proof we fill in the missing values by defining  $\dot{S}_\xi = \hat{\emptyset}$  for  $\xi \in A \setminus F$ . ▲<sub>2.3</sub>

### 3. RADIN FORCING

As we commented in the preamble, our proof involves Radin forcing. There are several accounts of this forcing in the literature (see [12], [11], [3], [6] and [7]), each subtly different from the others, and it turns out that it does matter which version of the forcing we use. Although the proofs of the various properties of the forcing are easiest, or at least slickest, for the versions given in Cummings-Woodin ([3]) and in Gitik ([6]), using either of these here creates technical difficulties. Consequently, we shall define and use a version of Radin forcing which, except for one small alteration to which we draw attention below, closely follows that of Mitchell in [11].

First of all, we give, by induction on  $\kappa \in \text{Card}$ , the definition of the set of *ultrafilter sequences at  $\kappa$* .

**Definition 3.1.** Let  $\kappa$  be a cardinal and let  $\mathcal{U}_\kappa$  be the collection of ultrafilter sequences at cardinals smaller than  $\kappa$ . A sequence  $u, = \langle u_\tau \mid \tau < \text{lh}(u) \rangle$ , is an *ultrafilter sequence at  $\kappa$*  if  $\text{lh}(u)$  is a non-zero ordinal,  $u_0 = \kappa$ , so that, using the notation of the introduction,  $\kappa_u = \kappa$ , and, for  $\tau \in (0, \text{lh}(u))$ , each  $u_\tau$  is a  $\kappa$ -complete ultrafilter on  $V_\kappa$  with  $\mathcal{U}_\kappa \in u_\tau$  and satisfies the following *normality* and *coherence* conditions (with respect to  $u$ ):

(*normality*) if  $f : \mathcal{U}_\kappa \rightarrow V_\kappa$  and  $\{w \in \mathcal{U}_\kappa \mid f(w) \in V_{\kappa_w}\} \in u_\tau$  then there is some  $x \in V_\kappa$  such that  $\{w \in \mathcal{U}_\kappa \mid f(w) = x\} \in u_\tau$ .

(*coherence 1*) if  $f : \mathcal{U}_\kappa \rightarrow \kappa$  and  $\{w \in \mathcal{U}_\kappa \mid f(w) < \text{lh}(w)\} \in u_\tau$  there is  $\sigma < \tau$  such that  $u_\sigma = \{X \subseteq V_\kappa \mid \{w \in \mathcal{U}_\kappa \mid X \cap V_{\kappa_w} \in w_{f(w)}\} \in u_\tau\}$ .

(*coherence 2*) if  $\sigma < \tau$  and  $X \in u_\sigma$  then  $\{w \in \mathcal{U}_\kappa \mid \exists \bar{\sigma} < \text{lh}(w) X \cap V_{\kappa_w} \in w_{\bar{\sigma}}\} \in u_\tau$ .

**Definition 3.2.** The class  $\mathcal{U}$  is the class of all ultrafilter sequences on any cardinal:  $\mathcal{U} = \bigcup_{\kappa \in \text{Card}} \mathcal{U}_\kappa$ .

**Definition 3.3.** For clarity we re-iterate the following special cases of notation of Definition (3.1):  $\mathcal{U}_{\kappa^+}$  is the set of ultrafilter sequences at cardinals less than or equal to  $\kappa$  and  $\mathcal{U}_{\kappa^+} \setminus \mathcal{U}_{\kappa}$  is the set of ultrafilter sequences at  $\kappa$ .

**Observation 3.4.** As Mitchell comments in [11], by the coherence properties, if  $u \in \mathcal{U}$  and  $\text{lh}(u) \leq \kappa_u$  then for  $\tau \in (0, \text{lh}(u))$  one has that  $u_\tau$  concentrates on  $\{w \in \mathcal{U}_{\kappa_u} \mid \text{lh}(w) = \tau\}$  (i.e.,  $\{w \in \mathcal{U}_{\kappa_u} \mid \text{lh}(w) = \tau\} \in u_\tau$ ).

**Observation 3.5.** We need some large cardinal assumption in order to construct non-trivial ultrafilter sequences. For the purposes of this paper we can use a construction due to Radin [12]. Let  $j : V \rightarrow M$  witness that  $\kappa$  is  $2^\kappa$ -supercompact. Derive a sequence  $u$  by setting  $u_0 = \kappa$  and then  $u_\alpha = \{X \subseteq V_\kappa \mid u \upharpoonright \alpha \in j(X)\}$  for  $\alpha > 0$ . One can verify that for every  $\alpha < (2^\kappa)^+$  we have  $u \upharpoonright \alpha \in \mathcal{U}_{\kappa}$ . In fact we will only need ultrafilter sequences of length less than  $\kappa$  in the sequel.

**Definition 3.6.** If  $u \in \mathcal{U}$  then  $\mathcal{F}(u) = \bigcap_{\tau \in (0, \text{lh}(u))} u_\tau$ .

**Definition 3.7.** A *pair* is some  $(u, A)$  with  $u \in \mathcal{U}$  and  $A \in \mathcal{F}(u)$  if  $\text{lh}(u) > 1$  and  $A = \emptyset$  if  $\text{lh}(u) = 1$ .

(Note that our notation thus far is marginally, but inessentially, different from that of [11]).

**Definition 3.8.** Let  $w \in \mathcal{U}$ .  $\mathbb{R}_w$ , *Radin forcing at  $w$* , has as conditions sequences of pairs  $\langle (u_0, B_0), \dots, (u_n, B_n) \rangle$  such that  $u_n = w$ , and, writing  $\kappa_i$  for  $\kappa_{u_i}$ ,  $(u_i, B_i) \in \mathcal{U}_{\kappa_{i+1}}$  and  $B_{i+1} \cap V_{\kappa_i^+} = \emptyset$  for  $i < n$ .

Let  $p = \langle (u_0, B_0), \dots, (u_n, B_n) \rangle$  and  $q = \langle (v_0, D_0), \dots, (v_m, D_m) \rangle \in \mathbb{R}_w$ . Then  $q \leq p$  ( $q$  refines  $p$ ) if  $m \geq n$  and

- (i) For every  $i \leq n$  there is  $j \leq m$  such that  $u_i = v_j$  and  $D_j \subseteq B_i$ .
- (ii) For every  $j \leq m$ , either  $v_j = u_i$  for some  $i$  or for the least  $i$  such that  $\kappa_{v_j} < \kappa_{u_i}$ ,  $v_j \in B_i$  and  $D_j \subseteq B_i$ .

We also define  $q \leq^* p$  if  $\langle u_i \mid i \leq n \rangle = \langle v_i \mid i \leq n \rangle$  and for each  $i \leq n$  we have  $D_i \subseteq B_i$ . We say that  $q$  is a (*Radin*-)direct extension of  $p$ . Thus  $q \leq^* p$  implies  $q \leq p$ .

**Definition 3.9.** Let  $p = \langle (u_0, B_0), \dots, (u_n, B_n) \rangle$  be a condition in  $\mathbb{R}_{u_n}$ . A pair  $(u, B)$  appears in  $p$  if there is some  $i \leq n$  such that  $(u, B) = (u_i, B_i)$ . Similarly an ultrafilter sequence  $u$  appears in  $p$  if there is some  $i \leq n$  such that  $u = u_i$ .

Thus clause (ii) in the definition of  $\leq$  in Definition (3.8) reads: if  $v_j$  does not appear in  $p$  and  $i$  is minimal such that  $\kappa_{v_j} < \kappa_{u_i}$  then  $v_j \in B_i$  and  $D_j \subseteq B_i$ .

**Observation 3.10.** [11] omits the last clause in the definition of what it is to be a condition. However our conditions form a dense subset of the conditions as defined in [11] and the facts that we quote from [11] are also true of our forcing. This minor change is advantageous for technical reasons in order to make the proof below run smoothly.

To help orient the reader, we record a few remarks (without proof) about the nature of the generic object for the forcing poset  $\mathbb{R}_w$ . This generic object is best viewed as a sequence  $\langle u_i \mid i < \delta \rangle$  where  $u_i \in \mathcal{U}_{\kappa_w}$  and  $\langle \kappa_{u_i} \mid i < \delta \rangle$  is increasing and continuous. When  $\text{lh}(w) > 1$  the sequence  $\langle \kappa_{u_i} \mid i < \delta \rangle$  is cofinal in  $\kappa_w$ , and we will view this sequence as enumerating a club set in  $\kappa_w$  which we call the *Radin-generic club set*. When  $i = 0$  or  $i$  is a successor ordinal then  $\text{lh}(u_i) = 1$ , otherwise  $\text{lh}(u_i) > 1$ . The translation between the generic sequence and the generic filter is given by the following.

**Definition 3.11.** Let  $G$  be an  $\mathbb{R}_w$ -generic filter over  $V$ . The sequence  $\langle u_i \mid i < \delta \rangle$  is the *corresponding generic sequence* if it enumerates  $\{u \in \mathcal{U}_{\kappa_w} \mid \exists p \in G \text{ } u \text{ appears in } p\}$ , i.e., the set of  $u \in \mathcal{U}_{\kappa_w}$  which appear in some condition in  $G$ .

**Lemma 3.12.** *Let  $G$  be an  $\mathbb{R}_w$ -generic filter over  $V$  and  $\langle u_i \mid i < \delta \rangle$  the corresponding generic sequence. Then*

$$G = \{p \in \mathbb{R}_w \mid \forall u \in \mathcal{U}_{\kappa_w} (u \text{ appears in } p \longrightarrow \exists i < \delta \text{ } u = u_i) \ \& \\ \forall i < \delta \exists q \leq p (u_i \text{ appears in } q)\},$$

i.e.  $G$  is the set of conditions  $p \in \mathbb{R}_w$  such that every  $u \in \mathcal{U}_{\kappa_w}$  which appears in  $p$  is among the sequences  $u_i$ , and every sequence  $u_i$  appears in some extension of  $p$ . ▲<sub>3.12</sub>

**Definition 3.13.** A *lower part* for  $\mathbb{R}_w$  is a condition in  $\mathbb{R}_u$  for some  $u \in \mathcal{U}_{\kappa_w}$ .

We note that any condition in  $\mathbb{R}_w$  has the form  $y \frown (w, B)$  where  $y$  is empty or a lower part for  $\mathbb{R}_w$ , and  $B \in \mathcal{F}(w)$ . In the case when  $y$  is non-empty we will say that  $y$  is the *lower part of  $y \frown (w, B)$* . It is easy to see that any two conditions with the same lower part are compatible, so that  $\mathbb{R}_w$  is the union of  $\kappa_w$ -many  $\kappa_w$ -complete filters and in particular it enjoys the  $\kappa_w^+$ -chain condition.

A key point is that below a condition of the form  $y \frown (w, B)$  with  $y$  non-empty, everything up to the last ultrafilter sequence appearing in  $y$  is controlled by pairs in  $y$ . More formally:

**Definition 3.14.** Let  $y = \langle (u_i, B_i) \mid i \leq n \rangle$ , be a lower part for  $\mathbb{R}_w$ . Then  $\kappa_y = \kappa_{u_n}$  and  $\mathbb{R}_y = \{q \in \mathbb{R}_{u_n} \mid q \leq y\}$ .

**Lemma 3.15.** Let  $p = y \frown (w, B)$  be a condition in  $\mathbb{R}_w$  with  $y$  non-empty. Then the subforcing  $\{q \in \mathbb{R}_w \mid q \leq p\}$  is isomorphic to the product  $\mathbb{R}_y \times \{q \in \mathbb{R}_w \mid q \leq (w, B \setminus \mathcal{U}_{\kappa_y^+})\}$ .

It follows from these considerations that if  $\langle u_i \mid i < \delta \rangle$  is a generic sequence for  $\mathbb{R}_w$  and  $\zeta < \delta$ , then  $\langle u_i \mid i < \zeta \rangle$  is a generic sequence for  $\mathbb{R}_{u_\zeta}$ . More generally, if there is a condition in the generic filter with lower part  $y$  then the generic sequence induces an  $\mathbb{R}_y$ -generic object in the natural way.

**Definition 3.16.** Let  $y$  be a lower part for  $\mathbb{R}_w$  and let  $G$  be  $\mathbb{R}_w$ -generic over  $V$ . We say that  $y$  *conforms with*  $G$  if and only if  $y$  is the lower part of some condition in  $G$ .

The following Lemma is a ‘‘local’’ version of Lemma (3.12).

**Lemma 3.17.** Let  $G$  be an  $\mathbb{R}_w$ -generic filter over  $V$  and let  $\langle u_i \mid i < \delta \rangle$  be the corresponding generic sequence. Let  $y = \langle (v_k, B_k) \mid k \leq n \rangle$  be a lower part. Then the following are equivalent:

- (1)  $y$  conforms with  $G$ .
- (2) For every  $k \leq n$  the sequence  $v_k$  appears among the sequences  $u_i$ , and for every  $i$  with  $\kappa_{u_i} \leq \kappa_{v_n}$  the ultrafilter sequence  $u_i$  appears in some extension of  $y$  in  $\mathbb{R}_y$ .

Moreover, if  $i < \delta$  then  $u_i$  appears in some lower part  $y'$  which conforms with  $G$  and with  $\kappa_{y'} = \max(\{\kappa_y, \kappa_{u_i}\})$ , and such that if  $y \frown (w, B) \in G$  there is some  $B' \in \mathcal{F}(w)$  such that  $y' \frown (w, B') \leq y \frown (w, B)$ . ▲<sub>3.17</sub>

The following result by Radin captures a key property of  $\mathbb{R}_w$

**Theorem 3.18** (Radin). (*The Prikry property for Radin forcing.*) Let  $p \in \mathbb{R}_w$  and let  $\phi$  be a sentence in the forcing language. Then either there is some  $p' \leq^* p$  such that  $p' \Vdash_{\mathbb{R}_w} \phi$  or there is some  $p' \leq^* p$  such that  $p' \Vdash_{\mathbb{R}_w} \neg \phi$ .

Combining Theorem (3.18) and Lemma (3.15), we obtain a lemma (due to Radin) which will be very important in the proof of  $\kappa^+$ -cc for the

main iteration. Recall that by our conventions a name for a truth value is just a name for an ordinal which is either 0 (false) or 1 (true).

**Lemma 3.19** (Radin). *Let  $y^\frown(w, B)$  be a condition in  $\mathbb{R}_w$  with  $y$  non-empty, and let  $\dot{b}$  be a  $\mathbb{R}_w$ -name for a truth value. Then there exist  $C \subseteq B$  with  $C \in \mathcal{F}(w)$  and a  $\mathbb{R}_y$  name for a truth value  $\dot{c}$  such that whenever  $G$  is  $\mathbb{R}_w$ -generic with  $y^\frown(w, C) \in G$  and  $G'$  is the induced generic object for  $\mathbb{R}_y$ , then  $(\dot{b})^G = (\dot{c})^{G'}$ .*

*Proof.* Using the factorisation given by Lemma (3.15) and the Product Lemma, we may view  $\dot{b}$  as an  $\mathbb{R}^*$ -name for a  $\mathbb{R}_y$ -name for a truth value where  $\mathbb{R}^* = \{q \in \mathbb{R}_w \mid q \leq (w, B \setminus \mathcal{U}_{\kappa_y^+})\}$ . Since  $|\mathbb{R}_y| < \kappa$  and a name for a truth value amounts to an antichain in  $\mathbb{R}_y$ , there are fewer than  $\kappa$  many  $\mathbb{R}_y$ -names for truth values. Since  $\mathcal{F}(w)$  is  $\kappa$ -complete we may appeal to the Prikry property for  $\mathbb{R}^*$ , and shrink  $(w, B \setminus \mathcal{U}_{\kappa_y^+})$  to  $(w, C)$  in order to decide which  $\mathbb{R}_y$ -name  $\dot{c}$  is in question. ▲<sub>3.19</sub>

In the situation of Lemma (3.19), we will sometimes say that the condition  $y^\frown(w, C)$  reduces the  $\mathbb{R}_w$ -name  $\dot{b}$  to the  $\mathbb{R}_y$ -name  $\dot{c}$ . Similar arguments (which we omit) about reducing names for sets of ordinals give another important result.

**Theorem 3.20** (Radin). *Let  $w \in \mathcal{U}$ , let  $G$  be  $\mathbb{R}_w$ -generic over  $V$  and let  $\langle u_j \mid j < \delta \rangle$  be the corresponding generic sequence. For every  $\alpha < \kappa_w$ , if  $i$  is largest such that  $\kappa_{u_i} \leq \alpha$ , then every subset of  $\alpha$  lying in  $V[G]$  lies in the  $\mathbb{R}_{u_i}$ -generic extension given by  $\langle u_j \mid j < i \rangle$ .*

It follows readily that forcing with  $\mathbb{R}_w$  preserves all cardinals. However cofinalities may change. The general situation is slightly complicated, the main point for us is given by the following result.

**Theorem 3.21** (Radin). *Let  $w \in \mathcal{U}$ , let  $G$  be  $\mathbb{R}_w$ -generic over  $V$  and assume that  $\text{lh}(w)$  is a regular cardinal  $\lambda$  with  $\lambda < \kappa_w$ . Let  $G$  be  $\mathbb{R}_w$ -generic. If  $\lambda$  is not a limit point of the Radin-generic club, then  $V[G] \models \lambda$  is regular and  $\text{cf}(\kappa) = \lambda$ .*

We note that the condition on  $\lambda$  in this theorem is easy to arrange by working below a suitable condition in  $\mathbb{R}_w$ . For example we may arrange that the least point of the generic club is greater than  $\lambda$ .

We will also require a characterisation of Radin-genericity which is due to Mitchell.



**Theorem 3.22** (Mitchell). *Let  $\langle u_i \mid i < \delta \rangle$  be a sequence of ultrafilter sequences in some outer model of  $V$ . Then the following are equivalent:*

- (1) *The sequence  $\langle u_i \mid i < \delta \rangle$  is  $\mathbb{R}_w$ -generic.*
- (2) *For every  $j < \delta$  the sequence  $\langle u_i \mid i < j \rangle$  is  $\mathbb{R}_{u_j}$ -generic, and if  $\text{lh}(w) > 1$  then  $\mathcal{F}(w) = \{X \in V \mid \exists j < \delta \forall i \ j < i < \delta \implies u_i \in X\}$  – i.e., if  $\text{lh}(w) > 1$  then  $\mathcal{F}(w)$  is the tail filter generated on the  $V$ -powerset of  $V_\kappa$  by the generic sequence.*

**Definition 3.23.** Sequences which satisfy the Mitchell criterion from Theorem (3.22) are sometimes called *geometric sequences*.

The following considerations will play a central rôle in the proof of Theorem (7.10).

**Observation 3.24.** Suppose that  $V \subseteq V'$  with  $V_\kappa^V = V_\kappa^{V'}$  (e.g.,  $V'$  might be a generic extension of  $V$  by  $<\kappa$ -closed forcing). Suppose that in  $V'$  there is an ultrafilter sequence  $w'$  such that  $\text{lh}(w) = \text{lh}(w')$  and  $w(\alpha) = w'(\alpha) \cap V$  for  $0 < \alpha < \text{lh}(w)$ . Let  $\langle u_i \mid i < \delta \rangle$  be a  $\mathbb{R}_{w'}$ -generic sequence over  $V'$ .

- By the Mitchell criterion for genericity and the observation that  $\mathcal{F}(w) \subseteq \mathcal{F}(w')$ , the sequence  $\langle u_i \mid i < \delta \rangle$  is also a  $\mathbb{R}_w$ -generic sequence over  $V$ .

**Lemma 3.25.** *Let  $G$  be an  $\mathbb{R}_w$ -generic filter over  $V$  and let  $\langle u_i \mid i < \delta \rangle$  be the corresponding generic sequence. Let  $y = \langle (v_k, B_k) \mid k \leq n \rangle$  be a lower part. Then the following are equivalent:*

- (1)  *$y$  conforms with  $G$ .*
- (2) *For every  $k$  the sequence  $v_k$  appears among the sequences  $u_i$ , and for every  $i$  with  $\kappa_{u_i} \leq \kappa_{v_n}$  either  $u_i$  appears among the sequences  $v_k$  or  $u_i \in B_k$  for the least  $k$  such that  $\kappa_{u_i} < \kappa_{v_k}$ .*

*Proof.* It is immediate that the first condition implies the second. For the converse direction, by Lemma (3.17), we need to verify that every sequence  $u_i$  with  $\kappa_{u_i} \leq \kappa_{v_n}$  appears in some element of  $\mathbb{R}_y$ . This is immediate when  $u_i$  appears among the  $v_k$ , so we assume that it does not and let  $k$  be least with  $\kappa_{u_i} < \kappa_{v_k}$ . If  $\text{lh}(u_i) = 1$  then we may extend  $y$  by shrinking  $B_k$  to  $B_k \setminus \mathcal{U}_{\kappa_{u_i}^+}$  and inserting the pair  $(u_i, \emptyset)$ . If  $\text{lh}(u_i) > 1$  then  $i$  is limit and by hypothesis  $u_j \in B_k$  for all large  $j < i$ , so that (by the geometric condition from part (2) of Theorem (3.22))  $B_k \cap V_{\kappa_{u_i}} \in \mathcal{F}(u_i)$ . In this case we may extend  $y$  by shrinking  $B_k$  to

$B_k \setminus \mathcal{U}_{\kappa_{u_i^+}}$  and inserting the pair  $(u_i, E)$  where  $E = B_0 \cap V_{\kappa_{u_i}}$  when  $k = 0$ , and  $E = B_k \cap V_{\kappa_{u_i}}$  when  $k > 0$ . ▲3.25

A very similar argument gives:

**Lemma 3.26.** *Let  $G$  be an  $\mathbb{R}_w$ -generic filter over  $V$  and let  $\langle u_i \mid i < \delta \rangle$  be the corresponding generic sequence. Let  $y \frown (w, B)$  be a condition. Then  $y \frown (w, B) \in G$  if and only if  $y$  conforms with  $G$  and  $u_i \in B$  for all  $i$  such that  $\kappa_{u_i} > \kappa_y$ .*

For use later we make a technical definition which is motivated by the Mitchell criterion for genericity, and will be used in the definition of the main iteration.

**Definition 3.27.** For  $y = \langle (u_i, B_i) \mid i < n \rangle$  a lower part for  $\mathbb{R}_w$ ,  $A = \langle A_\rho \mid \rho < \rho^* \rangle$  a sequence of subsets of  $V_{\kappa_w}$  and  $\eta < \kappa_w$  we say  $y$  is *harmonious with  $A$  past or above  $\eta$* , if for each  $i$  with  $i < n$  one of the following conditions holds.

- $\kappa_{u_i} < \eta$ .
- $\kappa_{u_i} = \eta$ ,  $u_i = \langle \eta \rangle$  and  $B_i = \emptyset$ .
- $\kappa_{u_i} > \eta$ , and  $\{u_i\} \cup B_i \subseteq \bigcup_{\rho < \rho^*} A_\rho \setminus \mathcal{U}_{\eta^+}$ .

**Observation 3.28.** We record some remarks about the preceding definition.

- If a lower part  $y$  is harmonious with  $A$  past  $\eta$  it divides rather strictly into a part below  $\eta$  and a part above: there is no  $(u_i, B_i)$  appearing in  $y$  such that  $\eta \leq \kappa_{u_i}$  while  $\kappa_v \leq \eta$  for some  $v \in B_i$ .
- Definition (3.27) depends only on the set  $\bigcup_{\rho < \rho^*} A_\rho$  rather than the sequence  $A$  itself. It is phrased in this way to avoid encumbering later definitions with union signs.

The following lemma shows how to thin a lower part conforming with a Radin generic sequence to one which still conforms and which is also harmonious past some  $\eta$  with a sequence of sets whose union contains the interval of the generic sequence consisting of those measure sequences with critical point at least  $\eta$  and which it can ‘see’. This, also, is useful for the proof of Theorem (7.10).

**Lemma 3.29.** *Let  $G$  be an  $\mathbb{R}_w$ -generic filter over  $V$  and let  $\langle u_i \mid i < \delta \rangle$  be the corresponding generic sequence. Let  $A = \langle A_\rho \mid \rho < \rho^* \rangle$  be such*

that each  $A_\rho$  is a set of measure sequences with a common critical point  $\kappa_\rho < \kappa$ , let  $a = \{\kappa_\rho \mid \rho < \rho^*\}$  and let  $D = \bigcup_{\rho < \rho^*} A_\rho$ .

Suppose that  $\eta$  is a successor point in the generic club set  $C$  such that  $u_i \in D$  for all  $i$  such that  $\eta \leq \kappa_{u_i} < \text{ssup}(a)$ .

Let  $y$  be a lower part conforming with  $G$  with  $\kappa_y < \text{ssup}(a)$ , and suppose that  $\langle \eta \rangle$  appears in  $y$ . Then there is a lower part  $y'$  such that

- (1)  $y'$  is a direct extension of  $y$  in  $\mathbb{R}_y$ ,
- (2)  $y'$  conforms with  $G$ , and
- (3)  $y'$  is harmonious with  $A$  past  $\eta$ .

*Proof.* By the definition of conformity all sequences appearing in  $y$  have the form  $u_i$  for some  $i$ . We will obtain  $y'$  by some judicious shrinking of the measure one sets appearing as the second entries of pairs in  $y$ .

Consider the pairs  $(v, B)$  appearing in  $y$ . If  $\kappa_v < \eta$  there is no problem, and if  $\kappa_v = \eta$  then (as  $\eta$  is a successor point in  $C$ ) we have  $v = \langle \eta_\varepsilon \rangle$  and  $B = \emptyset$ , so again there is no problem.

Suppose now that  $(v, B)$  appears in  $y$  and  $\kappa_v > \eta$ . By the definition of conditionhood,  $B$  contains no measure sequence  $u$  with  $\kappa_u \leq \eta$ . Let  $j$  be such that  $v = u_j$ , and recall that  $\text{lh}(v) = 1$  and  $B = \emptyset$  for  $j$  a successor, and  $\text{lh}(v) > 1$  and  $B \in \mathcal{F}(v)$  for  $j$  a limit.

By hypothesis we have  $u_i \in D$  for all  $i$  such that  $\kappa_{u_i} \geq \eta$ ; it follows by the “geometric” criterion for genericity (see Theorem (3.22)) that if  $j$  is a limit then  $D \cap V_{\kappa_v} \in \mathcal{F}(v)$ . So when  $v = v_j$  for  $j$  a limit, we may shrink  $B$  to obtain a set  $B' = B \cap D$  with  $B' \in \mathcal{F}(v)$ . We define  $y'$  to be the resulting lower part. ▲<sub>3.29</sub>

**Lemma 3.30.** *If  $y$  is a lower part which is harmonious with  $A$  past  $\eta$  and  $y' \in \mathbb{R}_y$ , then  $y'$  is harmonious with  $A$  past  $\eta$ .*

*Proof.* We consider each pair  $(u, B)$  appearing in  $y'$ . If  $u$  already appears in  $y$  then we have that  $(u, B')$  appears in  $y$  for some  $B'$  such that  $B \subseteq B'$ , and it is easy to see that in all cases the harmoniousness conditions are satisfied. If  $u$  does not appear in  $y$  then let  $(v, C)$  be the unique pair appearing in  $y$  such that  $u \in C$ , and consider the various cases of the definition for the pair  $(v, C)$ : if  $\kappa_v < \eta$  then  $\kappa_u < \eta$  and we are done, the case  $\kappa_v = \eta$  cannot occur as  $C \neq \emptyset$ , and if  $\kappa_v > \eta$  then  $\{u\} \cup B \subseteq C \subseteq \bigcup_{\rho < \rho^*} A_\rho \setminus \mathcal{U}_{\eta^+}$ . ▲<sub>3.30</sub>

4. THE DEFINITION OF  $Q(w)$ , AND USEFUL PROPERTIES OF IT.

Suppose that  $U$  is a measure on a measurable cardinal  $\kappa$ . Recall that  $\kappa$ -Mathias forcing using  $U$  has as conditions pairs  $(s, S)$  with  $s \in [\kappa]^{<\kappa}$ ,  $S \in U$  and  $\text{ssup}(s) \leq \min(S)$  and ordering given by  $(t, T) \leq (s, S)$  if  $s = t \cap \text{ssup}(s)$  and  $T \cup (t \setminus s) \subseteq S$ . This forcing preserves cardinals as it is  $<\kappa$ -directed closed and has the  $\kappa^+$ -chain condition. If  $G$  is a generic filter over  $V$  for the forcing and  $y = \bigcup \{s \mid \exists S \in U (s, S) \in G\}$  then for all  $S \in \mathcal{P}(\kappa)$  we have that  $S \in U$  if and only if there is some  $\alpha < \kappa$  such that  $y \setminus \alpha \subseteq S$ . Consequently, the forcing is also known as the forcing to *diagonalise*  $U$ .<sup>1</sup>

We also recall Ellentuck's topologically inspired notation that if  $(s, S)$  is a condition in this forcing then  $[s, S] = \{y \in [\kappa]^\kappa \mid s \subseteq y \subseteq s \cup S\}$ . Using this notation we have that  $(t, T) \leq (s, S)$  if and only if  $[t, T] \subseteq [s, S]$ .

In this section we define two forcing posets. The first poset  $M(w)$  is the analogue of the  $\kappa$ -Mathias forcing for ultrafilter sequences  $w$ ; it will diagonalise the filter  $\mathcal{F}(w)$ . The second poset  $Q(w)$  is the variant of  $M(w)$  which is tailored, in the style of the analogous forcing from [4], to deal with Radin forcing names for graphs, and binary relations more generally, on  $\kappa^+$ .

One can view  $\kappa$ -Mathias forcing as adding a subset  $y$  of  $\kappa$  which is potentially a member of  $U'$  for some normal measure  $U'$  extending  $U$  in some generic extension. In the same spirit,  $M(w)$  is designed to add a set  $A \subseteq V_{\kappa_w}$  which is potentially a member of  $\mathcal{F}(w')$  for some sequence  $w'$  in a  $< \kappa_w$ -closed generic extension where  $\text{lh}(w') = \text{lh}(w)$  and  $w'_i \supseteq w_i$  for  $0 < i < \text{lh}(w)$ .

For the rest of this section we fix an ultrafilter sequence  $w$  with  $\text{lh}(w) > 1$ , and write  $\kappa$  for  $\kappa_w$ .

**Definition 4.1.**  $M(w)$  is the forcing with conditions  $p = (A, B)$ , with:

- $A = \langle A_\rho \mid \rho < \rho^p \rangle$ , where  $\rho^p < \kappa$ ,
- $\forall \rho < \rho^p (A_\rho \subseteq \mathcal{U}_\kappa \ \& \ A_\rho \neq \emptyset \ \& \ \exists \kappa_\rho < \kappa \ \forall u \in A_\rho \ \kappa_u = \kappa_\rho)$ ,
- $\forall \rho < \rho^p \ \forall u \in A_\rho \ \forall \tau \in (0, \text{lh}(u)) \ u \upharpoonright \tau \in A_\rho$ ,
- $\langle \kappa_\rho \mid \rho < \rho^p \rangle$  is strictly increasing,
- $B \in \mathcal{F}(w)$ ,
- $\forall v \in B \ \forall \tau \in (0, \text{lh}(v)) \ (v \upharpoonright \tau \in B)$ , and

<sup>1</sup>It has also sometimes been called *long Prikry forcing*.

- $\text{ssup}(\{\kappa_\rho \mid \rho < \rho^p\}) \leq \min(\{\kappa_v \mid v \in B\})$ .

If  $p, q \in M(w)$  then  $q \leq p$  if  $A^p = A^q \upharpoonright \rho^p$  and  $B^q \cup \bigcup_{\rho \in [\rho^p, \rho^q]} A_\rho^q \subseteq B^p$ , while  $q \leq^* p$  if  $q \leq p$  and  $A^q = A^p$ . If  $p, q \in M(w)$  and  $q \leq^* p$  we say that  $q$  is a *direct extension* of  $p$ .

**Definition 4.2.** Set  $[A^p, B^p]$  to be

$$\begin{aligned} & \{ \langle D^\rho \mid \rho < \kappa \rangle \mid \forall \rho < \kappa (D^\rho \subseteq \mathcal{U}_\kappa \ \& \ \exists \kappa_\rho < \kappa \forall u \in D^\rho (\kappa_u = \kappa_\rho) \ \& \\ & \forall u \in D^\rho \forall \tau \in (0, \text{lh}(u)) (u \upharpoonright \tau \in D^\rho) \ \& \ \langle \kappa_\rho \mid \rho < \kappa \rangle \text{ is strictly} \\ & \text{increasing} \ \& \ \langle D^\rho \mid \rho < \rho^p \rangle = A^p \ \& \ \bigcup \{ D^\rho \mid \rho \in [\rho^p, \kappa] \} \subseteq B^p \}. \end{aligned}$$

Then  $(A^q, B^q) \leq (A^p, B^p)$  if and only if  $[A^q, B^q] \subseteq [A^p, B^p]$ .

It is useful to have a name for the set of cardinals which are the first elements of the various ultrafilter sequences appearing anywhere in  $A^p$  for  $p \in M(w)$ . Accordingly we make the following definition.

**Definition 4.3.** If  $p = (A, B) \in M(w)$  let  $a^p = \{\kappa_\rho \mid \rho < \rho^p\}$ .

Now we move on to the definition of the forcing  $Q(w)$ . This is carried out under the following running combinatorial assumption.

**Setting 4.4.** Suppose  $\mathcal{T}$  is a binary  $\kappa^+$ -Kurepa tree with  $\Upsilon$  many branches.

**Definition 4.5.** Let  $\langle b_\alpha \mid \alpha < \Upsilon \rangle$  enumerate of a set of branches through  $\mathcal{T}$ . Let  $\langle \dot{E}_\alpha \mid \alpha < \Upsilon \rangle$  be a list of canonical  $\mathbb{R}_w$ -names for binary relations on  $\kappa^+$ . We will use the sequences  $\langle b_\alpha \mid \alpha < \Upsilon \rangle$  and  $\langle \dot{E}_\alpha \mid \alpha < \Upsilon \rangle$  as parameters in the definition of the forcing  $Q(w)$ .

$Q^*(w)$  is the forcing with conditions  $p = (A, B, t, f)$  satisfying the following four clauses.

- (1)  $(A, B) \in M(w)$  (see Definition (4.1)). We set  $a = a^{(A, B)}$ .
- (2)  $t \in [(a \cap \text{sup}(a)) \times \Upsilon]^{< \kappa}$  and  $f = \langle f_\alpha^\eta \mid (\eta, \alpha) \in t \rangle$ . For  $\eta \in a \cap \text{sup}(a)$ , set  $t^\eta = \{\alpha \mid (\eta, \alpha) \in t\}$ .
- (3)  $\forall \eta \in a \cap \text{sup}(a) \forall \alpha \in t^\eta d_\alpha^\eta = \text{dom}(f_\alpha^\eta) \in [\kappa^+]^{< \kappa}$ .
- (4)  $\forall \eta \in a \cap \text{sup}(a) \forall \alpha \in t^\eta \forall \zeta \in d_\alpha^\eta \exists \nu < \kappa f_\alpha^\eta(\zeta) = (b_\alpha \upharpoonright \zeta, \nu)$ .

If  $p, q \in Q^*(w)$  then  $q \leq p$  if  $[A^q, B^q] \subseteq [A^p, B^p]$ ,  $t^p \subseteq t^q$  and  $\forall (\eta, \alpha) \in t^p (f_\alpha^\eta)^p \subseteq (f_\alpha^\eta)^q$ ; and  $q \leq^* p$  if  $q \leq p$  and  $A^q = A^p$ ,  $t^q = t^p$  and  $f^q = f^p$ . (If  $q \leq^* p$  we say  $q$  is a *direct extension* of  $p$ .)

We write  $Q(w)$  for the suborder of  $Q^*(w)$  consisting of conditions which also satisfy:

- (5) for all  $\eta \in a \cap \text{sup}(a)$ , for all  $\alpha, \beta \in t^\eta$ , for every lower part  $y$  for  $\mathbb{R}_w$  harmonious with  $A$  past  $\eta$ , and for all  $\zeta, \zeta' \in d_\alpha^\eta \cap d_\beta^\eta$  we have:

$$f_\alpha^\eta(\zeta) = f_\beta^\eta(\zeta) \neq f_\alpha^\eta(\zeta') = f_\beta^\eta(\zeta') \implies y \frown (w, B) \Vdash_{\mathbb{R}_w} \text{“} \zeta \dot{E}_\alpha \zeta' \longleftrightarrow \zeta \dot{E}_\beta \zeta' \text{”}.$$

**Observation 4.6.** Observe that in clause (5), if  $y = \langle (u_i, B_i) \mid i \leq n \rangle$  and  $y$  is harmonious with  $A$  past  $\eta$  for some  $\eta \in a$ , then  $\kappa_{u_n} \leq \text{sup}(a)$ .

**Observation 4.7.** It is important to remember that  $Q(w)$  and  $Q^*(w)$  depend on the tree  $\mathcal{T}$  and the sequences  $\langle b_\alpha \mid \alpha < \Upsilon \rangle$  and  $\langle \dot{E}_\alpha \mid \alpha < \Upsilon \rangle$  even though their names do not make this dependence explicit.

The poset  $Q(w)$  is designed to add a sequence  $A^*$  which diagonalises  $\mathcal{F}(w)$  in a sense made precise in Corollary (4.9) below, together with various objects that can potentially be understood as  $\mathbb{R}_{w^*}$ -names where  $w^*$  is an ultrafilter sequence existing in some  $<\kappa$ -directed closed forcing extension of  $V$ , with  $\text{lh}(w) = \text{lh}(w^*)$ ,  $w_\tau^* \cap V = w_\tau$  for  $0 < \tau < \text{lh}(w)$  and  $\bigcup A^* \in \mathcal{F}(w^*)$ .

The aim is that if  $\langle u_i \mid i < \eta \rangle$  is a  $\mathbb{R}_{w^*}$ -generic sequence (where we note that by the Mitchell criterion this sequence is also  $\mathbb{R}_w$ -generic) and  $u_i \in \bigcup A^*$  for all  $i$  such that  $\kappa_{u_i} \geq \eta$  (along with various other technical conditions), then the “ $\eta$ -coordinate” in the poset  $Q(w)$  will add a  $\mathbb{R}_{w^*}$  name for a binary relation of size  $\kappa^+$  together with embeddings of all the relations named by the names  $\dot{E}_\alpha$  into this relation.

We are particularly interested in the posets  $Q(w)$  for certain specific lists of relations, for example when  $\langle \dot{E}_\alpha \mid \alpha < \Upsilon \rangle$  is a list of canonical names for all graphs on  $\kappa^+$ . In this case the “ $\eta$ -coordinate” will add a name for a graph whose realization will be universal for the graphs named by the names in the list.

**Lemma 4.8.** *For every  $\varepsilon < \kappa$ , the set of  $q \in Q(w)$  such that  $\varepsilon < \kappa_\rho^q$  for some  $\rho < \rho^q$  is dense and open.*

*Proof.* It is immediate that this set is open, so we only need to verify that it is dense. Let  $p \in Q(w)$  and let  $\rho = \rho^p$ . Find  $v \in B^p$  such that  $\kappa_v > \max(\{\varepsilon, \text{sup}(a^p)\})$  and note that  $v \upharpoonright \tau \in B^p$  for  $0 < \tau \leq \text{lh}(v)$ .

Now let  $\rho^q = \rho + 1$ ,  $A^q \upharpoonright \rho = A^p$ ,  $A^q_\rho = \{v \upharpoonright \tau \mid 0 < \tau \leq \text{lh}(v)\}$ ,  $B^q = \{v' \in B^p \mid \kappa_{v'} > \kappa_v\}$ ,  $t^q = t^p$  and  $f^q = f^p$ .

We claim that  $q \in Q(w)$  and  $q \leq p$ . The only non-trivial point is to check that  $q$  satisfies Clause (5) in the definition of  $Q(w)$ . Let  $\eta, \alpha, \beta, \zeta, \zeta'$  be such that  $f^q_\alpha(\zeta) = f^p_\alpha(\zeta) \neq f^q_\alpha(\zeta') = f^p_\alpha(\zeta')$ , and note that since  $(\eta, \alpha) \in t^q = t^p$  we have that  $\eta \in a^p \cap \text{sup}(a^p)$ .

Let  $y$  be harmonious with  $A^q$  above  $\eta$ . If  $\kappa_y < \kappa_v$  then clearly  $y$  is harmonious with  $A^p$  above  $\eta$ , and we are done by Clause (5) for  $p$  and the remark that  $y \frown (w, B^q) \leq y \frown (w, B^p)$ . If  $\kappa_y = \kappa_v$  then we have  $y = y' \frown (v \upharpoonright \tau, D)$ , where  $\kappa_{y'} < \kappa_v$ ,  $y'$  is harmonious with  $A^p$  and also  $D \subseteq \bigcup_{\rho < \rho^p} A^p_\rho$ ; by the choice of  $\kappa_v$  to be  $> \text{sup}(a^p)$  we see that  $D$  is bounded in  $V_{\kappa_v}$  and so cannot be of measure 1 for any measure on  $v$ , hence necessarily  $\tau = 1$  and  $D = \emptyset$ , so that actually  $v \upharpoonright \tau = \langle \kappa_v \rangle$ . It follows that  $y \frown (w, B^q) \leq y' \frown (w, B^p)$ , and again we are done by Clause (5) for  $p$ .

▲4.8

**Corollary 4.9.** *If  $G$  is  $Q(w)$ -generic over  $V$  and  $A^*$  is the union of the sequences  $A^p$  for  $p \in G$ , then  $A^*$  is a  $\kappa$ -sequence and for every  $B \in \mathcal{F}(w)$  there is  $\rho^* < \kappa$  such that  $A^* \subseteq B$  for  $\rho^* < \rho < \kappa$ .*

The proof of Lemma (4.8) also gives the following result.

**Lemma 4.10.** *The set of  $p \in Q(w)$  such that  $\rho_p$  is a successor ordinal is dense in  $Q(w)$ .*

**Notation 4.11.** For  $\eta < \kappa$ ,  $\alpha < \Upsilon$  and  $\zeta < \kappa^+$  let  $\mathcal{D}^{\eta}_{\zeta, \alpha} = \{p \in Q \mid \alpha \in (t^\eta)^p \ \& \ \zeta \in (d^\eta_\alpha)^p\}$ .

**Lemma 4.12.** *Suppose  $p \in Q(w)$ ,  $\eta \in a^p$ .  $\alpha < \Upsilon$  and  $\zeta < \kappa^+$ . Then there is  $q \in \mathcal{D}^{\eta}_{\zeta, \alpha}$  with  $q \leq p$ ,  $A^q = A^p$ ,  $B^q = B^p$ ,  $(t^\eta)^q = (t^\eta)^p \cup \{\alpha\}$  and  $(d^\eta_\alpha)^q = (d^\eta_\alpha)^p \cup \{\eta\}$ . (Here we take  $(d^\eta_\alpha)^p = \emptyset$  if  $\alpha \notin (t^\eta)^p$ .)*

*Proof.* If  $p \in \mathcal{D}^{\eta}_{\zeta, \alpha}$  then take  $q = p$  and there is nothing more to do. So suppose that  $p \notin \mathcal{D}^{\eta}_{\zeta, \alpha}$ . If  $\alpha \notin (t^\eta)^p$  observe that  $\langle A^p, B^p, t^p \cup \{(\eta, \alpha)\}, f^p \frown \langle \emptyset \rangle \rangle$  is a condition in  $Q(w)$  and refines  $p$ . (The concatenated 1-tuple consisting of the empty set records that the value of the new  $f$ -part of the condition at the co-ordinate  $(\eta, \alpha)$  is the empty function.) Consequently we may assume without loss of generality that  $\alpha \in (t^\eta)^p$  and  $\zeta \notin (d^\eta_\alpha)^p$ .

Pick  $\nu \in \kappa \setminus \bigcup \{\text{rge}((\pi_1 \cdot f^\eta_\beta)^p) \mid (\eta, \beta) \in t^p\}$ , let  $(f^\eta_\alpha)^q = (f^\eta_\alpha)^p \cup \{\langle \zeta, (b_\alpha \upharpoonright \zeta, \nu) \rangle\}$  and set  $(f^\eta_{\beta'})^q = (f^\eta_{\beta'})^p$  for  $(\eta', \beta) \in t^p$  with  $(\eta', \beta) \neq (\eta, \alpha)$ . Then  $q = \langle A^p, B^p, t^p, \langle (f^\eta_\beta)^q \mid (\eta, \beta) \in t^p \rangle \rangle$  is clearly an element of

$Q^*(w)$  and refines  $p$ . Moreover,  $q$  satisfies (5) of the definition of  $Q(w)$  since if  $(\eta, \beta) \in t^q$ ,  $\zeta' \in (d_\beta^\eta)^q$  we have that  $\nu$  was chosen specifically so that  $(f_\alpha^\eta)^q(\zeta) \neq (f_\beta^\eta)^p(\zeta')$ .  $\blacktriangle_{4.12}$

**Corollary 4.13.** *For each  $\eta < \kappa$ , each  $\alpha < \Upsilon$  and each  $\zeta \in \kappa^+$ , the set  $\mathcal{D}_{\zeta, \alpha}^\eta = \{p \in Q \mid \alpha \in (t^\eta)^p \ \& \ \zeta \in (d_\alpha^\eta)^p\}$  is dense and open in  $\{p \in Q(w) \mid \eta \in a^p\}$ .*

*Proof.* Immediate from Lemma (4.12).  $\blacktriangle_{4.13}$

**Corollary 4.14.** *If  $G$  is  $Q(w)$ -generic over  $V$ ,  $\eta \in \bigcup\{a^p \mid p \in G\}$  and  $\alpha < \Upsilon$  then  $\bigcup\{f_\alpha^{p, \eta} \mid p \in G, (\eta, \alpha) \in t^p\}$  is a function with domain  $\kappa^+$ .*

**Lemma 4.15.**  *$Q(w)$  has splitting.*

*Proof.* This is proved using an argument very similar to the one for Lemma (4.12). As observed there, given a condition  $p$  we can easily find a condition in  $Q(w)$  refining it with a non-empty  $t$ -part, so without loss of generality we may as well assume  $t^p \neq \emptyset$ . Let  $(\eta, \alpha) \in t^p$ . Now pick  $\zeta \in \kappa^+ \setminus (d_\alpha^\eta)^p$  and working exactly as before we can define two extensions  $q_0, q_1$  of  $p$  which are both in  $\mathcal{D}_{\zeta, \alpha}^\eta$  but satisfy  $(f_\alpha^\eta)^{q_0}(\zeta) \neq (f_\alpha^\eta)^{q_1}(\zeta)$ , simply by choosing, at the ultimate stage of that argument, two distinct elements  $\nu_0$  and  $\nu_1$  of  $\kappa \setminus \bigcup_{(\eta, \beta) \in t^p} \text{rge}((f_\beta^\eta)^p)$ , where previously we merely picked one. Then  $q_0$  and  $q_1$  are incompatible.  $\blacktriangle_{4.15}$

**Lemma 4.16.** *The forcing poset  $Q(w)$  is  $<\kappa$ -compact.*

*Proof.* Let  $A = \{q_i \mid i < \mu\}$  be a centred subset of  $Q(w)$  for some  $\mu < \kappa$ , and fix for each finite set  $Y \subseteq \mu$  some condition  $s_Y \in Q(w)$  such that  $s_Y \leq q_i$  for all  $i \in Y$ . We will define a quadruple  $(A^*, B^*, t^*, f^*)$  of the appropriate type, and prove that it is a condition in  $Q(w)$  and forms a lower bound for  $A$ .

- Let  $\rho^* = \sup\{\rho^{q_i} \mid i < \mu\}$ . By the hypothesis it is easy to see that there is a unique sequence  $A^* = \langle A_\rho \mid \rho < \rho^* \rangle$  such that  $A^* \upharpoonright \rho^{q_i} = A^{q_i}$  for all  $i < \mu$ . We write  $\kappa_\rho$  for the common value of  $\kappa_v$  for sequences  $v \in A_\rho$ , and  $a^*$  for  $\{\kappa_\rho \mid \rho < \rho^*\}$ .
- Let  $B^* = \bigcap_{Y \in [\mu]^{<\omega}} B^{s_Y}$ . By the completeness of the filter  $\mathcal{F}(w)$  we see that  $B^* \in \mathcal{F}(w)$ . It is also clear from the definition of  $Q(w)$  that  $\kappa_\rho < \kappa_v$  for every  $\rho < \rho^*$  and every  $v \in B^*$ .
- Let  $t^* = \bigcup_{i < \mu} t^{q_i}$ . Clearly  $t^* \subseteq (a^* \cap \sup(a^*)) \times \Upsilon$  and  $|t^*| < \kappa$ .



- For each  $(\eta, \alpha) \in t^*$ , let

$$d_\alpha^{*,\eta} = \bigcup \{d_\alpha^{q_i,\eta} \mid (\eta, \alpha) \in t^{q_i}, i < \mu\}$$

- By the hypothesis it is easy to see that there is a unique sequence of functions  $f^* = \langle f_\alpha^{*,\eta} \mid (\eta, \alpha) \in t^* \rangle$  with  $\text{dom}(f_\alpha^{*,\eta}) = d_\alpha^{*,\eta}$ , and  $f_\alpha^{*,\eta}(\zeta) = f_\alpha^{q_i,\eta}(\zeta)$  for all  $\zeta \in d_\alpha^{q_i,\eta}$ ,

It should be clear that  $(A^*, B^*, t^*, f^*)$  is a condition in  $Q^*(w)$ , and that if  $(A^*, B^*, t^*, f^*)$  is a condition in  $Q(w)$  then it forms a lower bound for  $A$ . So to finish the proof, we must verify clause (5) in the definition of  $Q(w)$ .

Let  $\eta \in a^* \cap \text{sup}(a^*)$  with  $\eta < \text{sup}(a^*)$ , let  $\alpha, \beta \in t^{*,\eta}$ , let  $y = \langle (u_i, B_i) \mid i \leq n \rangle$  be a lower part harmonious with  $A^*$  past  $\eta$ , and let  $\zeta, \zeta' \in d_\alpha^{*,\eta} \cap d_\beta^{*,\eta}$  be such that  $f_\alpha^{*,\eta}(\zeta) = f_\beta^{*,\eta}(\zeta) \neq f_\alpha^{*,\eta}(\zeta') = f_\beta^{*,\eta}(\zeta')$ .

Choose a finite set  $Y$  large enough that

- There is  $i_0 \in Y$  with  $\eta \in a^{q_{i_0}}$ ,  $\eta < \text{sup}(a^{q_{i_0}})$  and  $\kappa_{u_n} \leq \text{sup}(a^{q_{i_0}})$ .
- There is  $i_1 \in Y$  with  $(\eta, \alpha) \in t^{q_{i_1}}$ , and  $\zeta \in d_\alpha^{q_{i_1},\eta}$ .
- There is  $i_2 \in Y$  with  $(\eta, \beta) \in t^{q_{i_2}}$ , and  $\zeta \in d_\beta^{q_{i_2},\eta}$ .
- There is  $i_3 \in Y$  with  $(\eta, \alpha) \in t^{q_{i_3}}$ , and  $\zeta' \in d_\alpha^{q_{i_3},\eta}$ .
- There is  $i_4 \in Y$  with  $(\eta, \beta) \in t^{q_{i_4}}$ , and  $\zeta' \in d_\beta^{q_{i_4},\eta}$ .

Now consider the condition  $s_Y$ . By construction  $y$  is harmonious with  $A^{s_Y}$  past  $\eta$ , and since  $s_Y \in Q(w)$  it follows easily that

$$y \frown (w, B^{s_Y}) \Vdash_{\mathbb{R}_w} \text{“} \zeta \dot{E}_\alpha \zeta' \longleftrightarrow \zeta \dot{E}_\beta \zeta' \text{”}.$$

By construction  $B^* \subseteq B^{s_Y}$ , and so  $y \frown (w, B^*)$  also forces this equivalence and we are done.

**Corollary 4.17.**  *$Q(w)$  is both  $<\kappa$ -directed closed and countably compact.*

The following corollary to the proof of Lemma (4.16) and subsequent lemma are useful in the proof that  $Q(w)$  has the stationary  $\kappa^+$ -chain condition which appears in the next section.

**Corollary to the proof 4.18.** *Descending sequences from  $Q(w)$  of length less than  $\kappa$  have greatest lower bounds.*

**Lemma 4.19.** *Let  $p = (A, B, t, f) \in Q(w)$ . Let  $t = \bigcup\{t^\eta \mid \eta \in a^p\}$  and let  $\mathcal{d} = \bigcup\{d_\alpha^\eta \mid \eta \in a^p \ \& \ \alpha \in t^\eta\}$ . Then there is  $q \in Q(w)$  with  $q \leq p$ ,  $A^q = A^p$ ,  $B^q = B^p$ ,  $t^q = t$  for all  $\eta \in a^p$  and  $(d_\alpha^\eta)^q = \mathcal{d}$  for all  $\eta \in a^p$  and  $\alpha \in t^\eta$ .*

*Proof.* By induction on  $t \times \mathcal{d}$ , using Lemma (4.12) at initial and successor stages and Corollary (4.18) at limits. ▲<sub>4.19</sub>

We now introduce the notion of a *weakening* of a condition.

**Definition 4.20.** Let  $p$  be a condition in  $Q(w)$  such that  $\rho^p$  is a successor ordinal and let  $\rho^* < \rho^p$ . We define the  $\rho^*$ -*weakening* of  $p$  to be the quadruple  $r = (A^r, B^r, t^r, f^r)$  where  $A^r = A^p \upharpoonright \rho^*$ ,  $a^r = \{\kappa_\rho^p \mid \rho < \rho^*\}$ ,  $B^r = B^p \cup \bigcup\{A_\rho^p \mid \rho^* \leq \rho < \rho^p\}$ ,  $t^r = \{(\eta, \alpha) \in t^p \mid \eta \in a^r \cap \text{sup}(a^r)\}$  and  $f^r = \langle f_\alpha^{p,\eta} \mid (\eta, \alpha) \in t^r \rangle$ . Then  $r \in Q(w)$  and  $p \leq r$ .

**Lemma 4.21.** *Let  $p \in Q(w)$  with  $\rho^p$  a successor ordinal, let  $\rho^* < \rho^p$  and let  $r$  be the  $\rho^*$ -weakening of  $p$ . Then*

- (1)  $r \in Q(w)$ ,
- (2)  $p \leq r$ ,
- (3) *and for every  $\eta \in a^r$  and every lower part  $y$  which is harmonious with  $A^r$  past  $\eta$ , if  $f_\alpha^{p,\eta}(\zeta) = f_\beta^{p,\eta}(\zeta) \neq f_\alpha^{p,\eta}(\zeta') = f_\beta^{p,\eta}(\zeta')$ , then  $y \frown (w, B^r) \Vdash \text{“}\zeta \dot{E}_\alpha \zeta' \iff \zeta \dot{E}_\beta \zeta' \text{”}$ .*

*Proof.* It is easy to see that  $r \in Q^*(w)$ , and that  $p$  refines  $r$  in  $Q^*(w)$ . Since  $f_\alpha^{p,\eta} = f_\alpha^{r,\eta}$  when  $(\eta, \alpha) \in t^r$ , Clause (3) in the conclusion implies that  $r$  satisfies Clause (5) in Definition (4.5) (and hence that  $r$  is in  $Q(w)$ ). It will therefore suffice to verify Clause (3).

Suppose for a contradiction that  $y \frown (w, B^r)$  does not force the desired equivalence, then there is an extension  $y' \frown (w, B)$  forcing that the equivalence is false. Shrinking  $B$  if necessary we may assume that  $B \subseteq B^p$ .

We will break up  $y'$  as  $y_0 \frown y_1 \frown y_2$ , where  $y_0 \in \mathbb{R}_y$ ,  $y_1$  consists of pairs  $(u, C)$  such that  $u$  is drawn from  $\bigcup\{A_\rho^p \mid \rho^* \leq \rho < \rho^p\}$ , and  $y_2$  consists of pairs  $(u, C)$  such that  $u$  is drawn from  $B^p$ . This is possible because, by the definition of extension in  $\mathbb{R}_w$ , all pairs  $(u, C)$  in  $y'$  with  $\kappa_u > \kappa_y$  have  $u \in B^r$ .

We claim that  $y_0 \frown y_1$  is harmonious with  $A^p$  above  $\eta$ . An appeal to Lemma (3.30) shows that  $y_0$  is harmonious with  $A^r$  above  $\eta$ , which handles the pairs appearing in  $y_0$ . Let  $(u, C)$  be a pair appearing in  $y_1$ ,

and observe that  $\eta \in a^r = \{\kappa_\rho^p \mid \rho < \rho^*\}$ , while  $u \in \{A_\rho^p \mid \rho^* \leq \rho < \rho^p\}$ , so that  $\eta < \kappa_{\rho^*} \leq \kappa_u$ . By the definition of the ordering of  $\mathbb{R}_w$  we have  $C \subseteq B^r$ , and since  $\kappa_u = \kappa_\rho$  for some  $\rho < \rho^p$  in fact  $C \subseteq \bigcup\{A_\rho^p \mid \rho^* \leq \rho < \rho^p\}$ . In particular as  $\eta < \kappa_{\rho^*}$  we have that  $C \cap V_{\eta+1} = \emptyset$ .

We claim that by shrinking measure one sets appearing in  $y_2$  (if necessary) we may assume that  $y' \widehat{\ } (w, B) \leq y_0 \widehat{\ } y_1 \widehat{\ } (w, B^p)$ . For pairs  $(u, C)$  appearing in  $y_2$  we have that  $u \in B^p$  and  $C \subseteq B^r = B^p \cup \bigcup\{A_\rho^p \mid \rho^* \leq \rho < \rho^p\}$ ; since  $\rho^p$  is a successor ordinal we have that  $\kappa_v \leq \kappa_{\rho^{p-1}} < \kappa_u$  for all  $v \in \bigcup\{A_\rho^p \mid \rho^* \leq \rho < \rho^p\}$ , so that we may shrink  $C$  to obtain a pair  $(u, D)$  with  $D \subseteq B^p$ .

Since  $y_0 \widehat{\ } y_1$  is harmonious with  $A^p$  above  $\eta$  and  $p$  is a condition,  $y_0 \widehat{\ } y_1 \widehat{\ } (w, B^p)$  forces the equivalence  $\zeta \dot{E}_\alpha \zeta' \iff \zeta \dot{E}_\beta \zeta'$ . This is a contradiction as  $y' \widehat{\ } (w, B)$  is an extension of  $y_0 \widehat{\ } y_1 \widehat{\ } (w, B^p)$  and forces that the same equivalence fails. ▲4.21

**Lemma 4.22.** *Let  $p$  and  $q$  be conditions in  $Q(w)$  with  $p \leq q$  and  $\rho_p$  a successor ordinal. Let  $\rho^q \leq \rho^* < \rho^p$  and let  $r$  be the  $\rho^*$ -weakening of  $p$ . Then  $p \leq r \leq q$ .*

*Proof.* By Lemma (4.21) we already know that  $p \leq r$  so we need only to check that  $r \leq q$ . It is routine to check that  $A^q \upharpoonright \rho^q = A^p \upharpoonright \rho^q = A^q$ ,  $t^r \supseteq t^q$ ,  $f_\alpha^{r,\eta} = f_\alpha^{p,\eta} \supseteq f_\alpha^{q,\eta}$  for all  $(\eta, \alpha) \in t^q$ , and finally  $B^r \cup \bigcup\{A_\rho^r \mid \rho^q \leq \rho < \rho^r\} = B^p \cup \bigcup\{A_\rho^p \mid \rho^q \leq \rho < \rho^p\} \subseteq B^q$ . ▲4.22

## 5. $Q(w)$ HAS THE STATIONARY $\kappa_w^+$ -CHAIN CONDITION

For the duration of this section we fix an ultrafilter sequence  $w$  with  $\text{lh}(w) > 1$ , and let  $\kappa = \kappa_w$ . As in the previous section, let  $\mathcal{T}$  be a  $\kappa^+$ -Kurepa tree, let  $\langle b_\alpha \mid \alpha < \Upsilon \rangle$  be an enumeration of a set of branches through  $\mathcal{T}$  and let  $\langle \dot{E}_\alpha \mid \alpha < \Upsilon \rangle$  be a list of canonical  $\mathbb{R}_w$ -names for binary relations on  $\kappa^+$ . Let  $Q = Q(w)$ .

**Notation 5.1.** For each  $\alpha < \kappa^+$  let  $\mathcal{T}_\alpha = \{x \in \mathcal{T} \mid \text{lh}(x) = \alpha\}$  and let  $e_\alpha : \mathcal{T}_\alpha \longrightarrow \overline{\overline{\mathcal{T}_\alpha}}$  be a bijection enumerating  $\mathcal{T}_\alpha$ .

As  $\mathcal{T}$  is a  $\kappa^+$ -Kurepa tree one has for  $\alpha < \kappa^+$  that  $\overline{\overline{\mathcal{T}_\alpha}} \leq \kappa$ .

**Notation 5.2.** For  $\alpha < \beta < \Upsilon$  let  $\Delta(\alpha, \beta)$  be the least  $\zeta$  such that  $b_\alpha \upharpoonright \zeta \neq b_\beta \upharpoonright \zeta$ .

**Notation 5.3.** If  $p = (A, B', t, f) \in Q$  and there are  $t \in [\Upsilon]^{<\kappa}$  and  $\mathcal{d} \in [\kappa^+]^{<\kappa}$  such that  $t = t^\eta$  for all  $\eta \in a$  and  $\mathcal{d} = \text{dom}(f_\alpha^\eta)$  for all

$\eta \in a$  and  $\alpha \in t$ , let  $Z^p$  be the set of all tuples  $(\eta, y, x, \zeta, \zeta', \delta, \delta')$  where  $\eta \in a \cap \text{sup}(a)$ ,  $y$  is a lower part harmonious with  $A$  past  $\eta$ ,  $x \in \mathcal{T}$ ,  $\zeta < \zeta' < \kappa^+$  and  $\zeta, \zeta' \in \mathcal{d}$  and  $\delta, \delta' < \kappa$ .

**Lemma 5.4.** *Suppose  $p' = (A, B', t, f) \in Q$  and there are  $t \in [\Upsilon]^{<\kappa}$  and  $\mathcal{d} \in [\kappa^+]^{<\kappa}$  such that  $t = t^\eta$  for all  $\eta \in a$  and  $\mathcal{d} = \text{dom}(f_\alpha^\eta)$  for all  $\eta \in a$  and  $\alpha \in t$ .*

*Then there is some  $B \in \mathcal{F}(w)$  with  $B \subseteq B'$ , so that  $p = (A, B, t, f) \leq p'$ , and such that whenever  $z = (\eta, y, x, \zeta, \zeta', \delta, \delta') \in Z^p$  and  $\alpha \in t$  is such that  $x = b_\alpha \upharpoonright \zeta'$ ,  $f_\alpha^\eta(\zeta) = (x \upharpoonright \zeta, \delta)$  and  $f_\alpha^\eta(\zeta') = (x, \delta')$  there is an  $\mathbb{R}_y$ -name  $\dot{\sigma}_z$  such that  $y^\frown(w, B)$  forces that  $\dot{\sigma}_z$  is the truth value of the assertion that  $\zeta \dot{E}_\alpha \zeta'$ .*

*Proof.* First of all notice that  $Z^p = Z^{p'}$ . For each  $z \in Z^p$  we may define a  $\mathbb{R}_w$ -name  $\dot{\tau}_z$  such that for all  $\alpha \in t$  with  $f_\alpha^{\eta, i}(\zeta) = (x \upharpoonright \zeta, \delta)$  and  $f_\alpha^{\eta, i}(\zeta') = (x, \delta')$ ,  $y^\frown(w, \overline{B}^i)$  forces that  $\dot{\tau}_z$  is the truth value of the assertion that  $\zeta \dot{E}_\alpha \zeta'$ . (Condition (5) in the definition of being a condition shows  $\dot{\tau}_z$  does not depend on  $\alpha$ .)

By Lemma (3.19), for each  $z \in Z^p$  there is a set  $B_z \subseteq \overline{B}$  such that  $y^\frown(w, B_z)$  reduces  $\dot{\tau}_z$  to an  $\mathbb{R}_y$ -name  $\dot{\sigma}_z$ . As  $\overline{Z}^p < \kappa$  any  $B \in \mathcal{F}(w)$  such that  $B \subseteq \bigcap_{z \in Z^p} B_z$  suffices. ▲5.4

**Proposition 5.5.**  *$Q$  has the stationary  $\kappa^+$ -chain condition.*

**Proof.** Let  $\{p^i \mid i < \kappa^+\} \in [Q]^{\kappa^+}$ . For each  $i < \kappa^+$  let  $p^i = (A^i, B^i, t^i, f^i)$ , write  $a^i$  for  $a^{p^i}$  and  $\rho^i$  for  $\rho^{p^i}$ , and for each  $\rho < \rho^i$  write  $\kappa_\rho^i$  for  $(\kappa_\rho)^{p^i}$ .

We start by tidying up, for each  $i < \kappa^+$ , the collection of domains of constituents of the  $f^i$ . We want to emphasize that this step in the argument is not strictly necessary. At the cost of a more elaborate case analysis below, proofs of the stationary chain condition can be given which do *not* rely on the forcing having the property of having greatest lower bounds for descending sequences of length less than  $\kappa$ , a property which we do use in carrying out this tidying up.

By applying Lemma (4.19) and then Lemma (5.4) we can find  $\{p^i \mid i < \kappa^+\} \in [Q]^{\kappa^+}$  such that for each  $i < \kappa^+$  we have  $p^i = (A^i, B^i, t^i, f^i) \leq p^i$  and there is some  $t^i \in [\Upsilon]^{<\kappa}$  and some  $\mathcal{d}^i \in [\kappa^+]^{<\kappa}$  such that

- $t^i = t^{\eta, i}$  for all  $\eta \in a^i$ ,
- $\mathcal{d}^i = \text{dom}(f_\alpha^{\eta, i})$  for all  $\eta \in a^i$  and  $\alpha \in t^i$ , and

- $B^i$  has the property stated in the conclusion of Lemma (5.4).

Now we make a plethora of auxiliary definitions for each  $i$ , set out in the table below.

Let  $\{\alpha_\gamma \mid \gamma < \gamma^*\}$  be an enumeration of  $\bigcup\{t^i \mid i < \kappa^+\}$ , for some  $\gamma^* \leq \kappa^+$ . Let  $\{\alpha_\gamma^i \mid \gamma < \gamma^i\}$  be the increasing enumeration of  $t^i$ , for some  $\gamma^i < \kappa$ , for each  $i < \kappa^+$ .

Next, for each  $i < \kappa^+$  and  $\eta \in a^i$  let

- $\theta_0^i = \text{ssup}(\{\gamma \mid \alpha_\gamma \in t^i\})$ ,  $\theta_1^i = \text{ssup}(d^i)$ ,
- $\Gamma^i = \{\Delta(\alpha, \alpha') \mid \alpha, \alpha' \in t^i\}$ ,  $\nu^i = \text{ssup}(\Gamma^i)$ ,
- $T^i = \{\gamma < i \mid \alpha_\gamma \in t^i\}$ ,  $\Delta^i = \Gamma^i \cap i$ ,  $D^i = d^i \cap i$ ,
- $Y^{\eta,i} = \{y \mid y \text{ is a lower part harmonious with } A^i \text{ past } \eta\}$ .
- $g^{\eta,i}(\zeta, \gamma) = (e_\zeta(\pi_0(f_{\alpha_\gamma}^{\eta,i}(\zeta))), \pi_1(f_{\alpha_\gamma}^{\eta,i}(\zeta)))$  for  $\gamma \in T^i$  and  $\zeta \in D^i$ .
- $X^{\eta,i} = \{\langle y, \varepsilon, \zeta, \zeta', F_\varepsilon^\eta, \dot{\sigma} \rangle \mid y \in Y^{\eta,i} \ \& \ \varepsilon < \gamma^i \ \& \ \zeta, \zeta' \in D^i \ \& \ \zeta < \zeta' \ \& \ \text{on setting } \alpha = \alpha_\varepsilon^i \text{ one has } F_\varepsilon^\eta : D^i \longrightarrow \kappa \times \kappa \text{ is given by } F_\varepsilon^\eta(\zeta^*) = (e_{\zeta^*}(\pi_0(f_{\alpha_\varepsilon}^{\eta,i}(\zeta^*))), \pi_1(f_{\alpha_\varepsilon}^{\eta,i}(\zeta^*))) \text{ for } \zeta^* \in D^i \ \& \ \text{letting } x = b_\alpha \upharpoonright \zeta', f_\alpha^{\eta,i}(\zeta) = (x \upharpoonright \zeta, \delta) \text{ and } f_\alpha^{\eta,i}(\zeta') = (x, \delta'), \text{ we have } \dot{\sigma} = \dot{\sigma}_{(y,x,\eta,\zeta,\zeta',\delta,\delta')}^i \}$ .

Recall that  $\pi_l$  is projection onto the  $l$ th co-ordinate, so in the definition of  $g^{\eta,i}$ , e.g.,  $\pi_0(b_{\alpha_\gamma} \upharpoonright \zeta, \nu) = b_{\alpha_\gamma} \upharpoonright \zeta$  and  $\pi_1(b_{\alpha_\gamma} \upharpoonright \zeta, \nu) = \nu$ , while  $e_\zeta$  is the function enumerating the  $\zeta$ th level of the  $\kappa^+$ -Kurepa tree  $\mathcal{T}$ , so that  $e_\zeta(b_{\alpha_\gamma} \upharpoonright \zeta) \in \kappa$ . Thus  $g^{\eta,i} : D^i \times T^i \longrightarrow \kappa \times \kappa$ .

Notice, also, that the various  $F_\varepsilon^\eta$ ,  $\dot{\sigma}$ ,  $x$ ,  $\delta$  and  $\delta'$  appearing in the definition of  $X^{\eta,i}$  are uniquely determined by  $i$ ,  $\eta$  and the  $\langle y, \varepsilon, \zeta, \zeta' \rangle$ .

For the convenience of the reader we record the types of the objects which we have just defined.  $\alpha_\gamma \in \Upsilon$  for  $\gamma < \gamma^* \leq \kappa^+$ ,  $\alpha_\gamma^i \in \Upsilon$  for  $\gamma < \gamma^i < \kappa$ ,  $\theta_0^i < \kappa^+$ ,  $\Gamma^i \in [\kappa^+]^{<\kappa}$ ,  $\nu^i < \kappa^+$ ,  $\theta_1^i < \kappa^+$ ,  $T^i \in [i]^{<\kappa}$ ,  $\Delta^i \in [i]^{<\kappa}$ ,  $D^i \in [i]^{<\kappa}$ ,  $Y^{\eta,i} \in V_\kappa$ , and  $g^{\eta,i}$  is a partial function of size less than  $\kappa$  from  $i \times i$  to  $\kappa \times \kappa$ .

Let  $h^*$  be an injection from  $V_\kappa \times ([\kappa^+]^{<\kappa} \times \text{Fn}(\kappa^+ \times \kappa^+, \kappa \times \kappa, \kappa) \times [\kappa^+]^{<\kappa} \times [\kappa^+]^{<\kappa} \times \kappa \times (V_\kappa \times \kappa \times \kappa^+ \times \kappa^+ \times V_\kappa \times \text{Fn}(\kappa^+, \kappa \times \kappa, \kappa))^{<\kappa}) \times \kappa$  into  $\kappa^+$ . Let  $C$  be the set of closure points of  $h^*$ . Let

$$\tilde{C} = \{j < \kappa^+ \mid \forall i < j (\theta_0^i, \theta_1^i, \nu^i < j)\} \cap C.$$

So  $C$  and  $\tilde{C}$  are club subsets relative to  $S_\kappa^{\kappa^+}$ .

Let  $h(i) = h^*(A^i, \langle (T^i, g^{\eta,i}, D^i, \Delta^i, \text{otp}(\mathbf{t}^i), X^{\eta,i}) \mid \eta \in a^i \rangle, \bar{\kappa}^i)$  for  $i \in \tilde{C} \cap S_\kappa^{\kappa^+}$  and  $h(i) = 0$  otherwise. Clearly  $h(i) < i$  for all nonzero  $i < \kappa^+$ .

Now suppose that  $i, j \in \tilde{C} \cap S_\kappa^{\kappa^+}$ ,  $i < j$ , and  $h(i) = h(j)$ . In particular we have that  $A^i = A^j$  (and hence  $a^i = a^j$ ) and  $\bar{\kappa}^i = \bar{\kappa}^j$ , that  $\theta_0^{\eta,i}, \theta_1^{\eta,i}, \nu^{\eta,i} < j$ , and finally for all  $\eta \in a^i$

$$\langle T^i, g^{\eta,i}, D^i, \Delta^i, \text{otp}(\mathbf{t}^i), X^{\eta,i} \rangle = \langle T^j, g^{\eta,j}, D^j, \Delta^j, \text{otp}(\mathbf{t}^j), X^{\eta,j} \rangle.$$

We prove a series of lemmas which together describe the common parts of  $p^i$  and  $p^j$ . Let  $A$  be the common value of  $A^i$  and  $A^j$  and  $a$  that of  $a^i$  and  $a^j$ .

**Lemma 5.6.** (a)  $(\mathbf{t}^j \setminus \mathbf{t}^i) \cap \{\alpha_\gamma \mid i \leq \gamma < j\} = \emptyset$ , and (b)  $\mathbf{t}^i \cap \mathbf{t}^j \subseteq \{\alpha_\gamma \mid \gamma < i\}$ .

*Proof.* Suppose  $\alpha_\gamma \in \mathbf{t}^j$ . If  $\gamma < j$  then  $\gamma \in T^j$ . But  $T^j = T^i$ , so  $\gamma \in T^i$ . Hence  $\gamma < i$  and  $\alpha_\gamma \in \mathbf{t}^i$ , proving (a). If  $\alpha_\gamma \in \mathbf{t}^i$  then  $\gamma < \theta_0^i < j$ . Thus if  $\alpha_\gamma \in \mathbf{t}^i \cap \mathbf{t}^j$  we have (b).  $\blacktriangle_{5.6}$

**Lemma 5.7.**  $\mathbf{d}^i \cap \mathbf{d}^j \subseteq i$ .

*Proof.* If  $\zeta \in \mathbf{d}^i \cap \mathbf{d}^j$  then  $\zeta < \theta_1^i < j$ . So  $\zeta \in \mathbf{d}^j \cap j = D^j = D^i = \mathbf{d}^i \cap i$ .  $\blacktriangle_{5.7}$

**Lemma 5.8.** If  $\eta \in a$  and  $\alpha \in \mathbf{t}^i \cap \mathbf{t}^j$  then  $f_\alpha^{\eta,i} \upharpoonright \mathbf{d}^i \cap \mathbf{d}^j = f_\alpha^{\eta,j} \upharpoonright \mathbf{d}^i \cap \mathbf{d}^j$ .

*Proof.* Let  $\eta \in a$ . By Lemma (5.6) and Lemma (5.7), if  $\alpha = \alpha_\gamma$  then  $\mathbf{d}^i \cap \mathbf{d}^j \subseteq D^i = D^j = \text{dom}(g^{\eta,i}(\cdot, \gamma)) = \text{dom}(g^{\eta,j}(\cdot, \gamma))$ . As  $\alpha \in \mathbf{t}^i \cap \mathbf{t}^j$ , if  $\zeta \in \mathbf{d}^i \cap \mathbf{d}^j$  we have  $\mathbf{t}(\pi_0(f_\alpha^{\eta,i}(\zeta))) = \mathbf{t}(\pi_0(f_\alpha^{\eta,j}(\zeta)))$  and, as  $\mathbf{t}$  is a bijection,  $\pi_0(f_\alpha^{\eta,i}(\zeta)) = \pi_0(f_\alpha^{\eta,j}(\zeta)) = b_\alpha \upharpoonright \zeta$ . Hence we have the claimed agreement.  $\blacktriangle_{5.8}$

Recall that  $f^i + f^j$  is the unique function  $f$  such that  $\text{dom}(f) = \text{dom}(f^i) \cup \text{dom}(f^j)$ ,  $f \upharpoonright \text{dom}(f^i) = f^i$  and  $f \upharpoonright \text{dom}(f^j) = f^j$ .

Let  $q = (A, B^i \cap B^j, \mathbf{t}^i \cup \mathbf{t}^j, f^i + f^j)$ .

**Lemma 5.9.** The quadruple  $q$  is a condition in  $Q^*$ .

*Proof.* Recall that we defined  $A = A^i = A^j$ . Lemma (5.8) shows that  $f^i$  and  $f^j$  are compatible.  $\blacktriangle_{5.9}$

**Lemma 5.10.**  $\Gamma^i \cap \Gamma^j \subseteq i$ .

*Proof.* If  $\zeta \in \Gamma^i \cap \Gamma^j$  then  $\zeta < \nu^i < j$ . So  $\zeta \in \Delta^j$ . But  $\Delta^j = \Delta^i$ , so  $\zeta < i$ . ▲5.10

**Notation 5.11.** For  $\alpha \in \mathbf{t}^i \cup \mathbf{t}^j$  define  $d_\alpha^q = \mathbf{d}^i \cup \mathbf{d}^j$  if  $\alpha \in \mathbf{t}^i \cap \mathbf{t}^j$ ,  $d_\alpha^q = \mathbf{d}^i$  if  $\alpha \in \mathbf{t}^i \setminus \mathbf{t}^j$ , and  $d_\alpha^q = \mathbf{d}^j$  if  $\alpha \in \mathbf{t}^j \setminus \mathbf{t}^i$ .

**Lemma 5.12.** For  $\alpha \in \mathbf{t}^i \cup \mathbf{t}^j$  and  $\eta \in a$  we have  $d_\alpha^q = \text{dom}(f_\alpha^{\eta,q})$ .

*Proof.* Immediate from the definitions of  $q$  and the  $d_\alpha^q$ . ▲5.12

**Lemma 5.13.** Suppose  $\alpha, \beta \in \mathbf{t}^i \cap \mathbf{t}^j$ ,  $\zeta, \zeta' \in d_\alpha^q \cap d_\beta^q$ ,  $\zeta < \zeta'$ ,  $\eta \in a$  and  $f_\alpha^{\eta,q}(\zeta) = f_\beta^{\eta,q}(\zeta) \neq f_\alpha^{\eta,q}(\zeta') = f_\beta^{\eta,q}(\zeta')$ . Then  $\zeta, \zeta' \in \mathbf{d}^i \cap \mathbf{d}^j$ .

*Proof.* Let  $\alpha = \alpha_\gamma$  and  $\beta = \alpha_{\gamma'}$ . Then  $\gamma, \gamma' < i$  by Lemma (5.6) and  $\Delta(\alpha, \beta) \in \Gamma^i \cap \Gamma^j \subseteq i$ , by Lemma (5.10). Hence  $\zeta, \zeta' < i$  as  $b_\alpha \upharpoonright \zeta = \pi_0(f_\alpha^{\eta,q}(\zeta)) = \pi_0(f_\beta^{\eta,q}(\zeta)) = b_\beta \upharpoonright \zeta$  and similarly for  $\zeta'$ . Thus  $\zeta' \in D^j = D^i \subseteq \mathbf{d}^i$ . Similarly  $\zeta \in \mathbf{d}^j$ . ▲5.13

Finally, we can now show that  $q$  satisfies (5) of the definition of  $Q$ .

**Lemma 5.14.** Suppose  $\alpha, \beta \in \mathbf{t}^i \cup \mathbf{t}^j$ ,  $\zeta, \zeta' \in d_\alpha^q \cap d_\beta^q$ ,  $\eta \in a$  and  $f_\alpha^{\eta,q}(\zeta) = f_\beta^{\eta,q}(\zeta) \neq f_\alpha^{\eta,q}(\zeta') = f_\beta^{\eta,q}(\zeta')$  and  $y$  is harmonious with  $A^q$  past  $\eta$ . Then  $y^\frown(w, B^q) \Vdash_{\mathbb{R}_w} \text{“} \zeta \dot{E}_\alpha \zeta' \iff \zeta \dot{E}_\beta \zeta' \text{”}$ .

*Proof.* If for some  $k \in \{i, j\}$  we have  $\alpha, \beta \in \mathbf{t}^k$  then, using Lemma (5.13) if  $\alpha, \beta \in \mathbf{t}^i \cap \mathbf{t}^j$ ,  $\zeta, \zeta' \in \mathbf{d}^k$ . As  $p^k \in Q$  we have  $y^\frown(w, B^k) \Vdash \text{“} \zeta \dot{E}_\alpha \zeta' \iff \zeta \dot{E}_\beta \zeta' \text{”}$ . But  $B^q = B^i \cap B^j \subseteq B^k$ , so  $y^\frown(w, B^q) \leq y^\frown(w, B^k)$  and  $y^\frown(w, B^q) \Vdash \text{“} \zeta \dot{E}_\alpha \zeta' \iff \zeta \dot{E}_\beta \zeta' \text{”}$ .

Otherwise, either we have  $\alpha \in \mathbf{t}^i \setminus \mathbf{t}^j$ ,  $\beta \in \mathbf{t}^j \setminus \mathbf{t}^i$  and  $\zeta, \zeta' \in \mathbf{d}^i \cap \mathbf{d}^j$ , or we have the symmetric case with the rôles of  $i$  and  $j$  exchanged. We treat the former; for the symmetric case exchange  $i$  and  $j$  throughout.

Suppose  $\beta$  is the  $\varepsilon$ -th element of  $\mathbf{t}^j$ . As  $\text{otp}(\mathbf{t}^i) = \text{otp}(\mathbf{t}^j)$ , we can define  $\beta'$  to be the  $\varepsilon$ -th element of  $\mathbf{t}^i$ . As  $X^{\eta,i} = X^{\eta,j}$  we have that the ‘ $F_\varepsilon^\eta$ ’ for the tuple that starts  $\langle y, \varepsilon, \zeta, \zeta', \dots \rangle$  is the same for both  $i$  and  $j$ . Hence  $e_{\zeta'} \cdot \pi_0 \cdot f_{\beta'}^{\eta,i}(\zeta') = e_{\zeta'} \cdot \pi_0 \cdot f_\beta^{\eta,j}(\zeta')$ . As  $e_{\zeta'}$  is a bijection and  $\pi_0$  is projection onto the first co-ordinate, this gives  $b_\beta \upharpoonright \zeta' = b_{\beta'} \upharpoonright \zeta'$ . Let  $x = b_\beta \upharpoonright \zeta' = b_{\beta'} \upharpoonright \zeta'$ ,  $f_{\beta'}^{\eta,i}(\zeta) = f_\beta^{\eta,j}(\zeta) = (x \upharpoonright \zeta, \delta)$ ,  $f_{\beta'}^{\eta,i}(\zeta') = f_\beta^{\eta,j}(\zeta') = (x, \delta')$ , and, finally,  $z = (\eta, y, x, \zeta, \zeta', \delta, \delta')$ .

Then  $z \in Z^{p^i} \cap Z^{p^j}$ , and  $\dot{\sigma}_z^i = \dot{\sigma}_z^j = \dot{\sigma}$  say, where  $\dot{\sigma}$  is an  $\mathbb{R}_y$ -name for a truth value. Since  $B^q = B^i \cap B^j$ ,  $y^\frown(w, B^q)$  simultaneously reduces the truth values of the statements “ $\zeta \dot{E}_\beta \zeta'$ ” and “ $\zeta \dot{E}_{\beta'} \zeta'$ ” to  $\dot{\sigma}$ , so

$y^\frown(w, B^q) \Vdash \zeta \dot{E}_{\beta'} \zeta' \iff \zeta \dot{E}_\beta \zeta'$ ". If  $\beta' = \alpha$  we are done. Otherwise, as  $p^i \in Q$  we also have that  $y^\frown(w, B^i) \Vdash \zeta \dot{E}_\alpha \zeta' \iff \zeta \dot{E}_{\beta'} \zeta'$ ", and hence  $y^\frown(w, B^q) \Vdash \zeta \dot{E}_\alpha \zeta' \iff \zeta \dot{E}_\beta \zeta'$ ", as required.  $\blacktriangle_{5.14}$

## 6. THE MAIN ITERATION

Let  $V$  be a model in which  $\kappa$  is supercompact,  $\lambda$  is a regular cardinal less than  $\kappa$ , and  $\chi$  is a successor cardinal with predecessor  $\chi^-$  such that  $\text{cf}(\chi^-) \geq \kappa^{++}$ . Suppose also that GCH holds in  $V$  and  $\diamond_\chi(S_{\kappa^+}^\chi)$  holds.

Let  $\mathbb{L}$  be the Laver iteration ([9]), as defined in  $V$ , making the supercompactness of  $\kappa$  indestructible under  $<\kappa$ -directed closed forcing.

Let  $\dot{e}$  be a canonical  $\mathbb{L}$ -name such that  $\Vdash_{\mathbb{L}} \dot{e} : \kappa \rightarrow V_\kappa$  is a bijection. "

Using Theorem (1.2), Lemma (1.4), Lemma (4.16) and Proposition (5.5), we will define an  $\mathbb{L}$ -name  $\dot{\mathbb{P}}_\chi$  so that  $\Vdash_{\mathbb{L}} \dot{\mathbb{P}}_\chi$  is an iteration of length  $\chi$  consisting of  $\dot{Q}_0$ , a name for the usual forcing to add a  $\kappa^+$ -Kurepa tree with  $\chi^-$ -many branches followed by a  $<\kappa$ -support iteration of  $<\kappa$ -directed closed, countably parallel-closed stationary  $\kappa^+$ -cc forcings each of size less than  $\chi$ ." The constituents of the iteration will depend on a fixed sequence  $\langle \dot{x}_\alpha \mid \alpha < \chi^- \rangle$  of  $\mathbb{L} * \dot{Q}_0$ -names for distinct branches through the  $\kappa^+$ -Kurepa tree. The iteration will add  $\chi$ -many subsets of  $\kappa$ , but at each intermediate stage  $2^\kappa = \chi^-$ . As we define the iteration we also build an enumeration of  $\mathbb{L} * \dot{\mathbb{P}}_\chi$  as  $\langle p_\xi \mid \xi < \chi \rangle$ . As  $\chi$  is a regular cardinal there will be a club set relative to  $S_{\geq \kappa}^\chi$  of  $\xi < \chi$  such that  $\mathbb{L} * \dot{\mathbb{P}}_\xi = \{p_\varepsilon \mid \varepsilon < \xi\}$ . We simultaneously inductively define  $\mathbb{L} * \dot{\mathbb{P}}_\xi$ -names  $\dot{S}_\xi$  as in §2 and derive  $\mathbb{L} * \dot{\mathbb{P}}_\xi$ -names  $\dot{u}^\xi$ .

As each  $\dot{S}_\xi$  is a canonical name for a subset of  $\xi$ , when  $\xi = \kappa \cdot \lambda \cdot \xi$  (ordinal multiplication) we can easily convert it into a name for a set of order type  $\lambda$  of sequences of  $\xi$  many subsets of  $\kappa$ . In order to do this, for each  $\tau < \lambda$ , set  $\dot{u}_{1+\tau}^\xi$  to be the name derived from  $\dot{S}_\xi$  for  $\{\dot{e} \text{ " } \{\eta < \kappa \mid \kappa \lambda \varepsilon + \kappa \tau + \eta \in \dot{S}_\xi \cap [\kappa \lambda \varepsilon + \kappa \tau, \widehat{\kappa \lambda \varepsilon + \kappa(\tau + 1)}]\} \mid \varepsilon < \xi\}$  and set  $\dot{u}^\xi = \hat{\kappa} \frown \langle \dot{u}_{1+\tau}^\xi \mid 1 + \tau < \lambda \rangle$ .

We use the sequence  $\dot{u}^\xi$  to help define the next stage in the iteration. Let  $\dot{\mathcal{U}}^\xi$  be a  $\mathbb{L} * \dot{\mathbb{P}}_\xi$ -name for the class of all ultrafilter sequences. (As for each  $\xi < \chi$  we have  $\Vdash_{\mathbb{L}} \dot{\mathbb{P}}_\xi$  is  $<\kappa$ -directed closed", we will have for all  $\xi < \xi' \leq \chi$  that  $\Vdash_{\mathbb{L} * \dot{\mathbb{P}}_{\xi'}} \dot{\mathcal{U}}_{\kappa}^{\xi'} = \dot{\mathcal{U}}_{\kappa}^{\xi}$ .)



If  $\text{cf}(\xi) = \kappa^+$ ,  $\mathbb{L} * \dot{\mathbb{P}}_\xi = \{p_\varepsilon \mid \varepsilon < \xi\}$ ,  $\xi = \kappa\lambda\xi$  and  $\Vdash_{\mathbb{L} * \dot{\mathbb{P}}_\xi} \text{“}\dot{u}^\xi \in \dot{\mathcal{U}}^\xi \text{ and } \dot{\kappa}_{\dot{u}^\xi} = \kappa\text{”}$  let  $\langle \dot{E}_\alpha^\xi \mid \alpha < \chi^- \rangle$  enumerate the canonical  $\mathbb{L} * \dot{\mathbb{P}}_\xi * \dot{\mathbb{R}}_{\dot{u}^\xi}$ -names for graphs on  $\kappa^+$  and let  $\dot{\mathbb{Q}}_\xi = \dot{Q}(\dot{u}^\xi)$ , where  $\dot{Q}(\dot{u}^\xi)$  is an  $\mathbb{L} * \dot{\mathbb{P}}_\xi$ -name for the forcing defined from  $\dot{u}^\xi$ ,  $\langle \dot{x}_\alpha \mid \alpha < \chi^- \rangle$  and  $\langle \dot{E}_\alpha^\xi \mid \alpha < \chi^- \rangle$  as in §4. Otherwise let  $\dot{\mathbb{Q}}_\xi$  name the trivial forcing.

Fix  $G$  which is  $\mathbb{L}$ -generic over  $V$  and  $H$  which is  $\dot{\mathbb{P}}_\chi^G$ -generic over  $V[G]$ . For  $\xi < \chi$  let  $H_\xi$  be the restriction of  $H$  to  $\dot{\mathbb{P}}_\xi^G$ , let  $\mathbb{Q}_\xi = \dot{\mathbb{Q}}_\xi^{G*H_\xi}$ , and let  $u^\xi = (\dot{u}^\xi)^{G*H_\xi}$ .

If  $V[G][H_\xi] \models u^\xi \in \mathcal{U}$ ,  $\kappa_{u^\xi} = \kappa$  and  $\text{lh}(u^\xi) = \lambda$ , let

- $K_\xi$  be the  $\mathbb{Q}(u^\xi)$ -generic over  $V[G][H_\xi]$  induced by  $H$ ,
- $A^\xi = \langle A_\rho \mid \rho < \kappa \ \& \ \exists p \in K_\xi \ A_\rho = (A_\rho)^p \rangle$ ,
- and  $a^\xi = \bigcup \{a^p \mid p \in K_\xi\}$ .

Fix an enumeration  $\langle \dot{D}_\xi \mid \xi < \chi \rangle$  of the  $\mathbb{L} * \dot{\mathbb{P}}_\chi$ -names for subsets of  $V_\kappa$  such that each  $\dot{D}_\xi$  is a  $\mathbb{L} * \dot{\mathbb{P}}_\xi$ -name.

Let  $j : V \rightarrow M$  witness that  $\kappa$  is  $2^\chi$ -supercompact, such that in the iteration  $j(\mathbb{L})$  we force with  $\dot{\mathbb{P}}_\chi$  at stage  $\kappa$  and then do the trivial forcing at all stages between  $\kappa$  and  $(2^\chi)^+$ . Let  $j(\mathbb{L}) = \mathbb{L} * \dot{\mathbb{P}}_\chi * \dot{\mathcal{L}}$ , where  $\dot{\mathcal{L}}$  is a  $\mathbb{L} * \dot{\mathbb{P}}_\chi$ -name and we note that by the choice of  $j$  we have  $\Vdash_{\mathbb{L} * \dot{\mathbb{P}}_\chi} \text{“}\dot{\mathcal{L}} \text{ is } <(2^\chi)^+\text{-closed. ”}$ .

We now carry out, in  $V[G][H]$ , an inductive construction of length  $\chi$  in which we build a chain of conditions  $(r_\xi, \dot{q}_\xi) \in \dot{\mathcal{L}}^{G*H} * j(\dot{\mathbb{P}}_\chi)$  for  $\xi < \chi$ . Note that forcing with  $\dot{\mathcal{L}}^{G*H}$  over  $V[G][H]$  always adds a generic embedding  $j : V[G] \rightarrow M[j(G)]$  – see [2, §9] – so that the name  $j(\dot{\mathbb{P}}_\chi)$  is well defined. The construction includes arranging for each  $\xi < \chi$  that  $\Vdash_{\dot{\mathcal{L}}^{G*H}} \text{“}\dot{q}_\xi \in j(\dot{\mathbb{P}}_\xi)\text{”}$  and that for all  $p \in H_\xi$  we have that  $r_\xi \Vdash_{\dot{\mathcal{L}}^{G*H}} \text{“}\dot{q}_\xi \leq j(p)\text{”}$ .

Define  $\mathfrak{U} = (\{v \in \mathcal{U} \mid \kappa_v = \kappa \ \& \ \text{lh}(v) \leq \lambda\})^{V[G][H]}$ . Then  $V[G][H] \models \bar{\mathfrak{U}} \leq ((2^{2^\kappa})^\lambda) = 2^\chi$ .

*Inductive case:*  $\xi = 0$  or limit  $\xi$ . By the  $<\chi$ -closure of  $\dot{\mathcal{L}}^{G*H} * j(\dot{\mathbb{P}}_\chi)$ , just choose some  $(r_\xi, \dot{q}_\xi)$  such that  $\Vdash_{\dot{\mathcal{L}}^{G*H}} \text{“}\dot{q}_\xi \in j(\dot{\mathbb{P}}_\xi)\text{”}$ , and for all  $\xi' < \xi$  we have  $(r_\xi, \dot{q}_\xi) \leq (r_{\xi'}, \dot{q}_{\xi'})$ . Then for each  $p \in H_\xi$  we have  $r_\xi \Vdash_{\dot{\mathcal{L}}^{G*H}} \text{“}\dot{q}_\xi \leq j(p)\text{”}$ .

*Inductive case:*  $\xi + 1$ . If  $\xi = 0$  then  $\mathbb{Q}_0$  is the usual forcing to add a  $\kappa^+$ -Kurepa tree with  $\Upsilon$ -many branches as computed in  $V[G]$ , and we

set  $r_1$  to be the trivial condition and  $\dot{q}_1$  to be a name for the greatest lower bound of the union of the pointwise image of the  $\mathbb{Q}_0$ -generic filter. We now assume that  $\xi > 0$ .

If  $V[G][H_\xi] \models u^\xi \notin \mathcal{U}$  or  $u^\xi \in \mathcal{U}$  but  $\kappa_{u^\xi} \neq \kappa$  or  $u^\xi \in \mathcal{U}$  and  $\kappa_{u^\xi} = \kappa$  but  $\text{lh}(u^\xi) \neq \lambda$  there is nothing to do and we can take  $(r_{\xi+1}, \dot{q}_{\xi+1}) = (r_\xi, \dot{q}_\xi \dot{\cap} \dot{1}_{j(\mathbb{Q}_\xi)})$ . So assume otherwise:  $V[G][H_\xi] \models u^\xi \in \mathcal{U}$ ,  $\kappa_{u^\xi} = \kappa$  and  $\text{lh}(u^\xi) = \lambda$ .

By the construction so far  $(r_\xi, \dot{q}_\xi) \Vdash_{\dot{L}^{G*H} * j(\dot{\mathbb{P}}_\chi)}$  “there is a lifting  $j : V[G][H_\xi] \rightarrow M[j(G)][j(H_\xi)]$  of  $j$ .”

As  $2^\chi$  is less than the closure of  $\dot{L}^{G*H} * j(\dot{\mathbb{P}}_\chi)$  we may, by shrinking if necessary, assume that there is some  $(r'_\xi, \dot{q}'_\xi) \leq (r_\xi, \dot{q}_\xi)$  such that  $(r'_\xi, \dot{q}'_\xi) \parallel$  “ $v \in j(\dot{D}_\xi)$ ” for every  $v \in \mathcal{U}$ .

**Definition 6.1.** If  $v \in \mathcal{U}^{V[G][H]}$ ,  $\text{lh}(v) = \lambda$  and for all  $\tau < \lambda$  we have  $v_\tau \cap V[G][H_\xi] = u^\xi_\tau$  we say  $v$  fills out  $u^\xi$ .

Note that if  $v$  fills out  $u^\xi$  then, a priori,  $v \in \mathcal{U}$ .

**Lemma 6.2.** Set  $\bar{B} = \bigcap \{j(B^a) \mid (A^a, B^a, t^a, f^a) \in K_\xi\}$ .

Suppose there is some  $v \in \mathcal{U}^{V[G][H]}$  which fills out  $u^\xi$  and for all  $\tau < \lambda$  we have  $v \upharpoonright \tau \in \bar{B}$ . Then there is a master condition for  $j(\mathbb{Q}_\xi)$ , for  $j$  and  $V[G][H_\xi]$ , such that on forcing below the condition we can lift  $j$  to a map  $j : V[G][H_\xi][K_\xi] \rightarrow M[j(G)][j(H_\xi)][j(K_\xi)]$  and have that for every  $v \in \mathcal{U} \cap \bar{B}$  filling out  $u^\xi$  and every  $\tau < \lambda$  we have  $v \upharpoonright \tau \in j(A^\xi)_\kappa$ .

*Proof.* We construct a suitable master condition  $p^* = (A^*, B^*, t^*, f^*)$ .

- $A^* = A^\xi \dot{\cap} \{v \upharpoonright \tau \mid \tau < \lambda \ \& \ v \in \bar{B} \cap (\mathcal{U}_{\kappa^+} \setminus \mathcal{U}_\kappa) \ \& \ v \text{ fills out } u^\xi\}$ .
- $B^* = \bar{B} \setminus \mathcal{U}_{\kappa^+}$ .
- $t^* = \kappa \times j^{\text{“}\Upsilon}$ .
- For each  $\eta \in a^\xi$  and  $\alpha < \Upsilon$ ,  $f_{j(\alpha)}^{*,\eta} = \bigcup \{j(f_\alpha^{p,\eta}) \mid p \in K_\xi\}$ .

We note that since  $f_\alpha^{p,\eta}$  is a partial function of size less than  $\kappa$ , and we have the density lemmas Lemma (4.8) and Lemma (4.13), it is easy to see that  $d_{j(\alpha)}^{*,\eta} = \text{dom}(f_{j(\alpha)}^{*,\eta}) = j^{\text{“}\kappa^+}$  and  $f_{j(\alpha)}^{*,\eta}(j(\zeta)) = j(f_\alpha^{p,\eta}(\zeta))$  for any  $p \in K_\xi$  such that  $(\eta, \alpha) \in t^p$ . We also note that  $a^{p^*} = a^\xi \cup \{\kappa\}$ .

It is routine to verify that  $p^* \in j(\mathbb{Q}_\xi^*)$  and that  $p^* \leq_{j(\mathbb{Q}_\xi^*)} j(q)$  for  $q \in K_\xi$ . If we can verify that  $p^*$  is a condition in  $j(\mathbb{Q}_\xi)$ , then it is immediate from its definition that  $p^*$  is a master condition of the type required.

So, in order to complete the proof, we must show that  $p^*$  satisfies (5) in the definition of  $j(\mathbb{Q}_\xi)$ .

Let  $\eta \in a^\xi$ , and suppose that  $f_{j(\alpha)}^{*,\eta}(j(\zeta)) = f_{j(\beta)}^{*,\eta}(j(\zeta)) \neq f_{j(\alpha)}^{*,\eta}(j(\zeta')) = f_{j(\beta)}^{*,\eta}(j(\zeta'))$  for some  $\alpha, \beta \in \Upsilon$  and  $\zeta, \zeta' \in \kappa^+$ . Let  $y$  be harmonious with  $A^*$  past  $\eta$ . If  $\kappa_y < \kappa$  let  $y' = y$ . Otherwise let  $y', \tau < \lambda$ ,  $v \in B^*$  which fills out  $u^\xi$ , and  $\bar{B} \in \mathcal{F}(v \upharpoonright \tau)$  be such that  $y = y' \frown (v \upharpoonright \tau, \bar{B})$ .

Using Lemma (4.10) and the definition of  $p^*$  we may find  $p \in K_\xi$  with  $\rho^p$  a successor ordinal such that

- $\eta \in a^p$  with  $\eta < \max(a^p)$ ,
- $\kappa_{y'} < \max(a^p)$ ,
- $(\eta, \alpha), (\eta, \beta) \in t^p$ ,
- $\zeta, \zeta' \in d_\alpha^{p,\eta} \cap d_\beta^{p,\eta}$ ,
- $f_\alpha^{p,\eta}(\zeta) = f_\beta^{p,\eta}(\zeta) \neq f_\alpha^{p,\eta}(\zeta') = f_\beta^{p,\eta}(\zeta')$ ,
- and  $y'$  is harmonious with  $A^p$  past  $\eta$ .

If  $y = y'$  we have that  $y$  is harmonious with  $A^p$  past  $\eta$  and

$$y \frown (j(u^\xi), B^*) \leq y \frown (j(u^\xi), j(B^p)) = j(y \frown (u^\xi, B^p)).$$

As  $p$  is a condition in  $\mathbb{Q}_\xi$  we have  $y \frown (u^\xi, B^p) \Vdash \dot{\zeta} \dot{E}_\alpha^\xi \dot{\zeta}' \longleftrightarrow \dot{\zeta} \dot{E}_\beta^\xi \dot{\zeta}'$ , and we are done by elementarity.

So we may assume that we are in the other case, that is  $y = y' \frown (v \upharpoonright \tau, \bar{B})$  for some  $v \in B^*$  which fills out  $u^\xi$ . We note that  $v \upharpoonright \tau \in B$ , since each of the sets  $B^q$  is closed under taking initial segments. Let  $\rho^* < \rho^p$  be minimal such that  $\max(\{\eta, \kappa_{y'}\}) < \kappa_{\rho^*}$ .

Since  $y$  was chosen to be harmonious with  $A^*$  past  $\eta$ ,  $B^* \cap V_\kappa = \emptyset$ , and  $\eta < \kappa = \kappa_v$ , we see that  $\bar{B} \subseteq \bigcup \{A_\rho^\xi \mid \eta < \kappa_\rho, \rho < \kappa\}$  and  $\kappa_v > \eta$  for all  $v \in \bar{B}$ . Since  $y' \frown (v \upharpoonright \tau, \bar{B})$  is a condition, we also have that  $\kappa_v > \kappa_{y'}$  for all  $v \in \bar{B}$ . So by the choice of  $\rho^*$ ,  $\bar{B} \subseteq \bigcup \{A_\rho^\xi \mid \rho^* \leq \rho < \kappa\}$ .

Since the condition  $p \in K_\xi$ ,  $A_\sigma = A_\sigma^p$  for  $\rho^* \leq \sigma < \rho^p$  and  $A_\sigma \subseteq B^p$  for  $\rho^p \leq \sigma < \kappa$ . It follows that  $\bar{B} \subseteq \bigcup \{A_\sigma^p \mid \rho^* \leq \sigma < \rho^p\} \cup B^p$ .

We now appeal to Lemma (4.21) to obtain the  $\rho^*$ -weakening of  $p$ , that is to say the condition  $q \in Q$  such that  $\rho^q = \rho^*$ ,  $p \leq q$ ,  $A^q = A^p \upharpoonright \rho^*$ ,  $B^q = \bigcup \{A_\sigma \mid \rho^* \leq \sigma < \rho^p\} \cup B^p$ ,  $t^q = \{(\eta', \alpha') \in t^p \mid \eta' \in a^q \cap \text{sup}(a^q)\}$  and  $f^q = \langle f_{\alpha'}^{p,\eta'} \mid (\eta', \alpha') \in t^q \rangle$ . Since  $p \leq q$  we have  $q \in K_\xi$ , and so  $B^* \subseteq j(B^q)$ . By the choice of  $\rho^*$ ,  $y'$  is harmonious with  $A^q$  past  $\eta$ .

By Lemma (4.21) the condition  $q$  enjoys a strengthened form of condition (5) in the statement of  $Q(w)$ , which implies in this case that

$$y' \frown (u^\xi, B^q) \Vdash \text{“ } \zeta \dot{E}_\alpha^\xi \zeta' \longleftrightarrow \zeta \dot{E}_\beta^\xi \zeta' \text{.”}$$

We claim that

$$y \frown (j(u^\xi), B^*) \leq y' \frown (j(u^\xi), j(B^q)) = j(y' \frown (u^\xi, B^q)).$$

The only non-trivial point is that the pair  $(v \upharpoonright \tau, \overline{B})$  can be added to the condition  $y' \frown (j(u^\xi), j(B^q))$ . This holds because  $v \upharpoonright \tau \in \overline{B} \subseteq j(B^q)$ , and  $\overline{B} \subseteq \bigcup \{A_\sigma^p \mid \rho^* \leq \sigma < \rho^p\} \cup B^p = B^q = j(B_q) \cap V_\kappa$ . As in the case when  $y = y'$ , we are now done by elementarity.  $\blacktriangle_{6.2}$

Having established the preceding Lemma, we can now complete the inductive step.

*Case (i).* There is some  $(r, \dot{q}) \leq (r'_\xi, \dot{q}'_\xi)$  with  $\Vdash_{\dot{L}^{G*H}} \dot{q} \in j(\dot{\mathbb{P}}_\xi)$  such that

$$(r, \dot{q}) \Vdash_{\dot{L}^{G*H} * j(\dot{\mathbb{P}}_\xi)} \text{“} \exists v \in \mathcal{U} (v \text{ fills out } u^\xi \ \& \ \forall \tau < \lambda \\ v \upharpoonright \tau \in \bigcap \{j(B^q) \mid (A^q, B^q, t^q, f^q) \in K_\xi\} \text{”}.$$

Let  $r_{\xi+1} = r$  and use Lemma (6.2) to choose  $\dot{q}_{\xi+1}$  such that  $\dot{q}_{\xi+1} \upharpoonright \xi = \dot{q}$ ,  $(r_{\xi+1}, \dot{q}_{\xi+1} \upharpoonright \xi) \Vdash \text{“} \dot{q}_{\xi+1}(\xi) \text{ is a lower bound for } j\text{“}K_\xi\text{”}$  and  $(r_{\xi+1}, \dot{q}_{\xi+1}) \Vdash \text{“} \text{for every } v \in \mathcal{U} \text{ which fills out } u^\xi \text{ and every } \tau < \lambda \text{ we have } v \upharpoonright \tau \in j(A^\xi)\text{”}$ .

*Case (ii).* Otherwise. Again, by the closure of  $\dot{L}^{G*H} * j(\dot{\mathbb{P}}_\chi)$ , let  $(r_{\xi+1}, \dot{q}_{\xi+1}) \leq (r'_\xi, \dot{q}'_\xi)$  be such that  $(r_{\xi+1}, \dot{q}_{\xi+1} \upharpoonright \xi) \Vdash \text{“} \dot{q}_{\xi+1}(\xi) \text{ is a lower bound for } j\text{“}K_\xi\text{”}$  since  $Q_{\xi+1}$  is trivial.  $\blacktriangle_{\text{Inductive construction}}$

When the construction is complete use the  $\chi$ -closure of  $\dot{L}^{G*H} * j(\dot{\mathbb{P}}_\chi)$  again and take a lower bound  $(r^*, \dot{q}^*)$  for  $\langle (r_\xi, \dot{q}_\xi) \mid \xi < \chi \rangle$  such that for all  $q \in H$  we have  $r^* \Vdash \dot{q}^* \leq j(q)$ . Thus  $(r^*, \dot{q}^*)$  forces that  $j$  can be lifted to some  $j : V[G][H] \longrightarrow M[j(G)][j(H)]$ .

**Claim 6.3.** *If we generate  $u = \langle u_\tau \mid \tau < \lambda \rangle$  from such a lifting of  $j$  to  $V[G][H]$  in the usual way, by inductively, for  $\tau < \lambda$ , setting  $u_\tau = \{D \in V[G][H] \mid u \upharpoonright \tau \in j(D)\}$ , then in fact we have  $u \in V[G][H]$  (and not merely  $u \in V[G][H][j(G)][j(H)]$ ) and  $u \in \mathcal{U}^{V[G][H]}$ .*

*Proof.* This is true by closure and the fact that for all  $D$  we have  $D \in u_\tau$  if and only if  $(r^*, \dot{q}^*) \Vdash u \upharpoonright \tau \in j(D)$ .

We actually have that  $u$  is defined by induction on  $\lambda$  (all in  $V[G][H]$ ) as follows. First of all, set  $u_0 = \kappa$ . Then, suppose that for some  $\tau < \lambda$  we have constructed  $u_\sigma$  for all  $\sigma < \tau$  and  $V[G][H] \models \langle u_\sigma \mid \sigma < \tau \rangle \in \mathcal{U}$ .

We made sure for each  $\xi < \chi$  that  $(r^*, \dot{q}^*) \parallel \langle u_\sigma \mid \sigma < \tau \rangle \in j(\dot{D}_\xi)$ . So if  $u_\tau = \{D^{G*H} \mid (r^*, \dot{q}^*) \Vdash_{\dot{L}^{G*H}*j(\mathbb{P}_\chi)} \langle u_\sigma \mid \sigma < \tau \rangle \in j(\dot{D})\}$  then  $V[G][H] \models \text{“}u_\tau \text{ is a normal measure on } V_\kappa\text{”}$ .

We check that  $\langle u_\sigma \mid \sigma < \tau + 1 \rangle \in \mathcal{U}$ . First of all, we need to check that  $\mathcal{U}_\kappa \in u_\tau$ , that is that  $(r^*, \dot{q}^*) \Vdash_{\dot{L}^{G*H}*j(\mathbb{P}_\chi)} \langle u_\sigma \mid \sigma < \tau \rangle \in j(\mathcal{U}_\kappa)$ .

This is clear because  ${}^x M[j(G)][j(H)] \subseteq M[j(G)][j(H)]$  by the Laver construction, and so the sequence is in  $M[j(G)][j(H)]$ .

We also need that normality and the two coherence conditions from Definition (3.1) hold for  $u_\tau$ .

Normality is true since if  $f : \mathcal{U}_\kappa \rightarrow V_\kappa$  is a function in  $V[G][H]$  and  $(r^*, \dot{q}^*) \Vdash_{\dot{L}^{G*H}*j(\mathbb{P}_\chi)} \text{“}j(f)(\langle u_\sigma \mid \sigma < \tau \rangle) \in V_\kappa\text{”}$  then there is some  $z \in V_\kappa$  such that  $(r^*, \dot{q}^*) \Vdash_{\dot{L}^{G*H}*j(\mathbb{P}_\chi)} \text{“}j(f)(\langle u_\sigma \mid \sigma < \tau \rangle) = z\text{”}$ . For coherence: if  $f : \mathcal{U}_\kappa \rightarrow \kappa$  and  $(r^*, \dot{q}^*) \Vdash_{\dot{L}^{G*H}*j(\mathbb{P}_\chi)} \text{“}j(f)(\langle u_\sigma \mid \sigma < \tau \rangle) < \tau\text{”}$  then for some  $\sigma < \tau$  we have  $z \in u_\sigma$  if and only if  $(r^*, \dot{q}^*) \Vdash_{\dot{L}^{G*H}*j(\mathbb{P}_\chi)} \text{“}(j(z) \cap V_\kappa) \in u^{j(f)(\langle u_\sigma \mid \sigma < \tau \rangle)}\text{”}$  which is true as  $j(z) \cap V_\kappa = z$ ; and if  $\tau' < \tau$  and  $z \in u_{\sigma'}$  then  $(r^*, \dot{q}^*) \Vdash_{\dot{L}^{G*H}*j(\mathbb{P}_\chi)} \text{“}\exists \sigma < \tau' j(z) \cap V_\kappa \in u_\sigma\text{”}$ .

▲6.3

**Claim 6.4.** *In  $V[G][H]$  there is a stationary set  $S \subseteq S_{\kappa^+}^\chi$  such that*

- *For every  $\xi \in S$  one has  $\text{lh}(u^\xi) = \lambda$  and for every  $\tau < \lambda$  that  $u_\tau \cap V[G][H_\xi] = u_\tau^\xi$ .*
- *For every  $\xi$  in the closure of  $S$ ,  $S \cap \xi \in V[G][H_\xi]$ .*
- *For every  $\xi \in S$ ,  $u^\xi \in \mathcal{U}_{\kappa^+}^{V[G][H_\xi]}$ .*
- *For every  $\xi \in S$ ,  $\{v \mid \exists \rho < \kappa v \in A_\rho^\xi\} \in \mathcal{F}(u)$ .*

*Proof.* Working in  $V[G][H]$ , define a set  $T \subseteq \chi$  corresponding to  $u$  by enumerating each  $u_\tau$  in order type  $\chi$  as  $\langle y_{\tau\xi} \mid \xi < \chi \rangle$  and setting  $T \cap [\kappa.\tau.\xi, \kappa.\tau.(\xi+1)) = \{\kappa.\tau.\xi + \eta \mid \eta \in y_{\tau\xi}\}$ . Appealing to Proposition (2.3), we may find a stationary set  $S \subseteq S_{\kappa^+}^\chi$  such that  $S$  satisfies the first two clauses of the claim.

For  $\xi \in S$  and  $0 < \tau < \lambda$ , we have that  $u_\tau^\xi$  is a measure on  $V_\kappa$  in  $V[G][H_\xi]$ . Since  $\mathcal{U}_\kappa^{V[G]} = \mathcal{U}_\kappa^{V[G][H]}$  it is clear that each  $u_\tau^\xi$  concentrates on  $\mathcal{U}_\kappa$ .

*Ad normality.* Suppose  $f : \mathcal{U}_\kappa \longrightarrow V_\kappa^{V[G][H_\xi]}$  and  $\{w \in \mathcal{U}_\kappa \mid f(w) \in V_{\kappa_w}\} \in u_\tau^\xi$ . As  $u_\tau^\xi \subseteq u_\tau$  we can apply normality for  $u$  to get some  $x \in V_\kappa$  such that  $\{w \in \mathcal{U}_\kappa \mid f(w) = x\} \in u_\tau$ . But  $x, f \in V[G][H_\xi]$ , hence  $\{w \in \mathcal{U}_\kappa \mid f(w) = x\} \in u_\tau \cap V_\kappa^{V[G][H_\xi]} = u_\tau^\xi$ .

*Ad coherence (i).* Suppose  $f : \mathcal{U}_\kappa \longrightarrow \kappa$  with  $f \in V[G][H_\xi]$  and  $\{w \in \mathcal{U}_\kappa \mid f(w) < \text{lh}(w)\} \in u_\tau^\xi$ . Again as  $u_\tau^\xi \subseteq u_\tau$  we can apply the first coherence condition for  $u$  to get some  $\sigma < \tau$  with  $x \in u_\sigma$  if and only if  $\{w \in U_\kappa \mid x \cap V_{\kappa_w} \in w_{f(w)}\} \in u_\tau$ . If  $x \in V[G][H_\xi]$ , so that  $x \in u_\sigma^\xi$ , then, recalling that  $f \in V[G][H_\xi]$ , we have  $\{w \in U_\kappa \mid x \cap V_{\kappa_w} \in w_{f(w)}\} \in V[G][H_\xi]$ , and hence  $\{w \in U_\kappa \mid x \cap V_{\kappa_w} \in w_{f(w)}\} \in u_\tau^\xi$ . Conversely, if  $\{w \in U_\kappa \mid x \cap V_{\kappa_w} \in w_{f(w)}\} \in u_\tau^\xi$  then, as  $u_\tau^\xi \subseteq u_\tau$ , we have  $x \in u_\sigma$ .

*Ad coherence (ii).* If  $\tau' < \tau$  and  $x \in u_{\tau'}^\xi$ , then  $\{w \in \mathcal{U}_\kappa \mid \exists \sigma < \text{lh}(w) x \cap V_{\kappa_w} \in w_\sigma\} \in u_\tau$  and the set is clearly in  $V[G][H_\xi]$  as  $x$  is, and hence is an element of  $u_\tau^\xi$ .

Finally, at each  $\xi \in S$  when we did the inductive construction of  $(r_{\xi+1}, \dot{q}_{\xi+1})$  we must have been in ‘Case (i)’ and used Lemma (6.2) because  $(r^*, \dot{q}^* \upharpoonright j(\xi))$  would be an appropriate witness. Consequently for all  $\tau < \lambda$  we have that  $u \upharpoonright \tau \in j(A^\xi)$ , and hence  $A^\xi \in \mathcal{F}(u)$ .  $\blacktriangle_{6.4}$

**Proposition 6.5.** *Let  $S \in V[G][H]$  be as given by Claim (6.4). Let  $\xi$  be a limit of elements of the set  $S$  of cofinality at least  $\kappa^+$ . For each  $\tau < \lambda$  let  $v_\tau = \bigcup \{u_\tau^\varepsilon \mid \varepsilon \in S \cap \xi\}$ . Then  $V[G][H_\xi] \models v$  is an ultrafilter sequence and  $\forall \varepsilon \in S \cap \xi A^\varepsilon \in \mathcal{F}(v)$ .*

*Proof.* By Claim (6.4) we have that  $S \cap \xi \in V[G][H_\xi]$ , thus  $v \in V[G][H_\xi]$ . It is clear that  $v$  is a sequence of measures concentrating on  $\mathcal{U}_\kappa^{V[G][H_\xi]}$ . In order to see that the normality and coherence conditions hold it is enough to observe that since  $\text{cf}(\xi) \geq \kappa^+$  we have that for each  $z \in \mathcal{P}(\kappa)$  and  $f : \mathcal{U}_\kappa \longrightarrow V_\kappa$  if  $z, f \in V[G][H_\xi]$  there is some  $\varepsilon \in S \cap \xi$  such that  $z, f \in V[G][H_\varepsilon]$ . Again by Claim (6.4) we have that  $A^\varepsilon \in \mathcal{F}(v)$ .  $\blacktriangle_{6.5}$

## 7. PROOF THAT WE DO GET SMALL UNIVERSAL FAMILIES

Let  $S \in V[G][H]$  be as given by Claim (6.4). As in Proposition (6.5), we choose  $\xi$  a limit point of  $S$  with  $\text{cf}(\xi) = \kappa^{++}$ . Let  $G * H_\xi$  be the  $\mathbb{L} * \dot{\mathbb{P}}_\xi$ -generic filter over  $V$  induced by  $G * H$ , and define an ultrafilter sequence  $v \in V[G * H_\xi]$  by setting  $v_\tau = \bigcup \{u_\tau^\varepsilon \mid \varepsilon \in S \cap \xi\}$  for  $0 < \tau < \lambda$ . Let  $g^*$  be  $\mathbb{R}_v$ -generic over  $V[G * H_\xi]$ . As we discussed in §3, by forcing below a suitable condition we may arrange that

- the generic object induced by  $g^*$  is a  $\lambda$ -sequence  $\langle u_i \mid i < \lambda \rangle$  of ultrafilter sequences,
- defining  $\kappa_i = \kappa_{u_i}$  for  $i < \lambda$ , the set  $C = \{\kappa_i \mid i < \lambda\}$  is a club subset of  $\kappa$ ,
- $\min(C) > \lambda$ , and so  $\text{cf}(\kappa) = \lambda$  in  $V[G * H_\xi * g^*]$ .

**Notation 7.1.** For  $\varepsilon \in S \cap \xi$  set  $H_\varepsilon$  to be the induced  $\mathbb{P}_\varepsilon$ -generic filter over  $V[G]$ ,  $Q_\varepsilon = \dot{Q}_\varepsilon^{G * H_\varepsilon}$ ,  $K_\varepsilon$  to be the  $Q_\varepsilon$  generic filter over  $V[G][H_\varepsilon]$  induced by  $G * H_\xi$ ,  $A^{*\varepsilon} = \langle A_\rho \mid \rho < \kappa \ \& \ \exists p \in K_\varepsilon (\rho < \rho^p \ \& \ A_\rho = A_\rho^p) \rangle$ ,  $\kappa_\rho^\varepsilon$  to be the common value of  $\kappa_w$  for  $w \in A_\rho^{*\varepsilon}$ , and  $a^{*\varepsilon} = \{\kappa_\rho^\varepsilon \mid \rho < \kappa\}$ .

As per Observation(3.24), the characterisation of genericity for Radin forcing implies that for every  $\varepsilon \in S \cap \xi$ , the sequence  $\langle u_i \mid i < \lambda \rangle$  is  $\mathbb{R}_{u^\varepsilon}$ -generic over  $V[G][H_\varepsilon]$ . Let  $g^\varepsilon$  be the  $\mathbb{R}_{u^\varepsilon}$ -generic filter over  $V[G][H_\varepsilon]$  induced by this sequence, so that easily  $g^\varepsilon = g^* \cap \mathbb{R}_{u^\varepsilon}$ .

Note that, by the characterisation of Radin-genericity from Theorem (3.22), for each  $\varepsilon \in S \cap \xi$ , since  $A^\varepsilon \in \mathcal{F}(v)$  by Proposition (6.5), we have that  $u_j \in \bigcup \{A_\rho^{*\varepsilon} \mid \rho < \kappa\}$  for all large  $j < \lambda$ . Let  $i_\varepsilon < \lambda$  be the least successor ordinal such that  $u_j \in \bigcup \{A_\rho^{*\varepsilon} \mid \rho < \kappa\}$  for  $j \geq i_\varepsilon$ , and let  $\eta_\varepsilon = \kappa_{u_{i_\varepsilon}}$ . Since  $\eta_\varepsilon$  is a successor point of the generic club  $C$ , the sequence  $u_{i_\varepsilon} = \langle \eta_\varepsilon \rangle$ .

We note that since  $u_{i_\varepsilon} = \langle \eta_\varepsilon \rangle \in \bigcup \{A_\rho^{*\varepsilon} \mid \rho < \kappa\}$ , we may define  $\sigma_\varepsilon$  as the unique  $\rho$  such that  $\langle \eta_\varepsilon \rangle \in A_\rho^{*\varepsilon}$ , and by definition we have  $\kappa_{u_{i_\varepsilon}} = \eta_\varepsilon = \kappa_{\sigma_\varepsilon}^\varepsilon$ . It follows that for any  $q \in K_\varepsilon$  with  $\sigma_\varepsilon < \rho^q$  we have that  $\langle \eta_\varepsilon \rangle \in A_{\sigma_\varepsilon}^q$  and  $\eta_\varepsilon \in a^q$ .

**Definition 7.2.** For  $\varepsilon \in S \cap \xi$  let  $\mathfrak{E}_\alpha^\varepsilon = (\dot{E}_\alpha^\varepsilon)^{G * H_\varepsilon * g^\varepsilon}$ , and, for  $\alpha < \chi^-$ , let  $\mathfrak{f}_\alpha^\varepsilon = \bigcup \{(f_\alpha^{\eta_\varepsilon})^q \mid q \in K_\varepsilon \ \& \ \alpha \in t^{q, \eta_\varepsilon}\}$ .

As we proved in Section 4,  $\mathfrak{f}_\alpha^\varepsilon$  is a function with domain  $\kappa^+$  such that  $\mathfrak{f}_\alpha^\varepsilon(\zeta) \in \{b_\alpha \upharpoonright \zeta\} \times \kappa$  for every  $\zeta < \kappa^+$ .

**Definition 7.3.** For each  $\varepsilon \in S \cap \xi$  and  $\alpha < \chi^-$  define  $\mathcal{E}_\alpha^\varepsilon$  on  $\text{rge}(\mathfrak{f}_\alpha^\varepsilon)$  by  $z \mathcal{E}_\alpha^\varepsilon z'$  if and only if  $\text{ht}(\pi_0(z)) \mathfrak{E}_\alpha^\varepsilon \text{ht}(\pi_0(z'))$ . That is,  $\mathcal{E}_\alpha^\varepsilon = \mathfrak{f}_\alpha^\varepsilon \text{``} \mathfrak{E}_\alpha^\varepsilon$ .

We now prove a short technical lemma which will allow us to give an equivalent characterization of  $\mathcal{E}_\alpha^\varepsilon$ , which in turn facilitates the proof that  $\mathcal{E}_\alpha^\varepsilon$  and  $\mathcal{E}_\beta^\varepsilon$  are coherent for  $\alpha \neq \beta$ .

**Lemma 7.4.** *Let  $\varepsilon \in S \cap \xi$ . Suppose  $y \frown (u^\varepsilon, D) \in g^\varepsilon$  and  $q = (A^q, B^q, t^q, f^q) \in K_\varepsilon$  are such that*

- $\rho^q$  is a successor ordinal.
- $\eta_\varepsilon, \kappa_y \leq \sup(a^q)$ .
- $B^q \subseteq D$ .

Then there is a lower part  $y'$  such that

- $y' \frown (u^\varepsilon, B^q) \leq y \frown (u^\varepsilon, D)$
- $y' \frown (u^\varepsilon, B^q) \in g^\varepsilon$ .
- $y'$  is harmonious with  $A^q$  past  $\eta_\varepsilon$ .

*Proof.* Let  $j_0 < \lambda$  be the largest ordinal such that  $\kappa_{u_{j_0}} \leq \max(a^q)$ . For all  $j$  with  $j_0 < j < \lambda$  we have that  $u_j \in \bigcup_{\sigma < \kappa} A_\sigma^{*\varepsilon}$  and  $\kappa_{u_j} > \max(a^q)$ , so that  $u_j \in B^q$ .

Appealing to the second part of Lemma (3.17) and to Lemma (3.26), we may now extend  $y \frown (u^\varepsilon, D)$  to a condition  $\bar{y} \frown (u^\varepsilon, B^q) \in g^\varepsilon$  by first adding in (as necessary) the pair  $(\langle \eta_\varepsilon \rangle, \emptyset)$  and a pair with first entry  $u_{j_0}$ , then shrinking  $D$  to  $B^q$ . Note that  $\kappa_{\bar{y}} = \max(\{\eta_\varepsilon, \kappa_y, \kappa_{u_{j_0}}\}) \leq \max(a^q)$ .

Appealing to Lemma (3.29), there is  $y'$  directly extending  $\bar{y}$  in  $\mathbb{R}_{\bar{y}}$  such that  $y'$  conforms with  $g^\varepsilon$ , and  $y'$  is harmonious with  $A^q$  past  $\eta_\varepsilon$ .  $\blacktriangle_{7.4}$

**Proposition 7.5.** *For each  $\varepsilon \in S \cap \xi$ ,  $\alpha < \chi^-$  and  $z, z' \in \text{rge}(f_\alpha^\varepsilon)$  we have  $z \mathfrak{E}_\alpha^\varepsilon z'$  if and only if there exist a condition  $p \in K_\varepsilon$  and a lower part  $y$  harmonious with  $A^p$  past  $\eta_\varepsilon$  such that  $p$  and  $y \frown (u^\varepsilon, B^p)$  witness that  $z \mathfrak{E}_\alpha^\varepsilon z'$ , i.e., letting  $\zeta = \text{lh}(\pi_0(z))$  and  $\zeta' = \text{lh}(\pi_0(z'))$ , such that*

- $\alpha \in t^{p, \eta_\varepsilon}$ ,  $\zeta, \zeta' \in d_\alpha^{p, \eta_\varepsilon}$ ,  $f_\alpha^{p, \eta_\varepsilon}(\zeta) = z$  and  $f_\alpha^{p, \eta_\varepsilon}(\zeta') = z'$ .
- $y$  is harmonious with  $A^p$  past  $\eta_\varepsilon$ .
- $y \frown (u^\varepsilon, B^p) \in g^\varepsilon$ .
- $y \frown (u^\varepsilon, B^p) \Vdash_{\mathbb{R}_{u^\varepsilon}}^{V[G][H_\varepsilon]} \zeta \dot{E}_\alpha^\varepsilon \zeta'$ .

*Proof.* If  $p$  and  $y$  are as in the equivalent, then  $y \frown (u^\varepsilon, B^p) \in g^\varepsilon$  and  $y \frown (u^\varepsilon, B^p) \Vdash_{\mathbb{R}_{u^\varepsilon}}^{V[G][H_\varepsilon]} \zeta \dot{E}_\alpha^\varepsilon \zeta'$ , so that  $\zeta \mathfrak{E}_\alpha^\varepsilon \zeta'$ .

For the converse direction, suppose that  $\zeta \mathfrak{E}_\alpha^\varepsilon \zeta'$ . Choose a condition  $y \frown (u^\varepsilon, D) \in g^\varepsilon$  such that  $y \frown (u^\varepsilon, D) \Vdash_{\mathbb{R}_{u^\varepsilon}}^{V[G][H_\varepsilon]} \zeta \dot{E}_\alpha^\varepsilon \zeta'$  and  $\langle \eta_\varepsilon \rangle$  appears in  $y$ . By the choice of  $\eta_\varepsilon$ , the sequence  $\langle \eta_\varepsilon \rangle$  and all subsequent sequences appearing in  $y$  are members of  $\bigcup_{\rho < \kappa} A_\rho^{*\varepsilon}$ .



Choose a condition  $q \in K^\varepsilon$  such that  $\eta_\varepsilon, \kappa_y \in a^q$ ,  $\rho^q$  is a successor ordinal, and  $B^q \subseteq D$ . Appealing to Lemma (7.4) we find a condition  $y' \frown (u^\varepsilon, B^q)$  which is exactly of the kind need to form a witness (together with  $q$ ) that  $z \mathcal{E}_\alpha^\varepsilon z'$ .  $\blacktriangle 7.5$

Next we show that  $\mathcal{E}_\alpha^\varepsilon$  and  $\mathcal{E}_\beta^\varepsilon$  cohere for  $\alpha \neq \beta$ .

**Lemma 7.6.** *Let  $\varepsilon \in S \cap \xi$ ,  $\alpha \neq \beta$  and  $z$  and  $z' \in \text{rge}(\mathfrak{f}_\alpha^\varepsilon) \cap \text{rge}(\mathfrak{f}_\beta^\varepsilon)$ . Then  $z \mathcal{E}_\alpha^\varepsilon z'$  if and only if  $z \mathcal{E}_\beta^\varepsilon z'$ .*

*Proof.* Choose  $r \in K_\varepsilon$  and  $y$  a lower part witnessing the equivalent conditions listed in Proposition (7.5) that  $z \mathcal{E}_\alpha^\varepsilon z'$ . Choose  $p \leq r$  such that  $p \in K^\varepsilon$ ,  $\rho^p$  is a successor ordinal, and  $p$  contains enough information to verify that  $z, z' \in \text{rge}(\mathfrak{f}_\alpha^\varepsilon)$ , that is to say that  $\beta \in t^{p, \eta_\varepsilon}$ ,  $\zeta, \zeta' \in d_\beta^{p, \eta_\varepsilon}$ ,  $f_\beta^{p, \eta_\varepsilon}(\zeta) = z$  and  $f_\beta^{p, \eta_\varepsilon}(\zeta') = z'$ .

We now recall the notion of  $\rho^*$ -weakening from Definition (4.20). Let  $q$  be the  $\rho^r$ -weakening of  $p$ , and note that by definition  $A^q = A^p \upharpoonright \rho^r = A^r$  and  $a^q = a^r$ . It follows from Lemmas (4.21) and (4.22) that  $p \leq q \leq r$ , in particular  $q \in K_\varepsilon$  and  $B^q \subseteq B^r$ .

We claim that  $y$  and  $B^q$  will serve as witnesses that  $z \mathcal{E}_\beta^\varepsilon z'$ , that is that  $y \frown (u^\varepsilon, B^q) \in g^\varepsilon$  and that  $y \frown (u^\varepsilon, B^q) \Vdash \zeta \dot{E}_\beta^\varepsilon \zeta'$ .

By Lemma (3.26), to check that  $y \frown (u^\varepsilon, B^q) \in g^\varepsilon$  we must show that  $y$  conforms with  $g^\varepsilon$  and  $u \in B^q$  for all  $u$  appearing on the generic sequence with  $\kappa_y < \kappa_u$ . Since  $y \frown (u^\varepsilon, B^r) \in g^\varepsilon$ , we see that the lower part  $y$  conforms with  $g^\varepsilon$  and also that  $u \in B^r$  for all  $u$  appearing on the generic sequence with  $\kappa_y < \kappa_u$ . Fix such a sequence  $u$ . Since  $r$  is a condition and  $u \in B^r$  it follows that  $\text{ssup}(a^q) = \text{ssup}(a^r) \leq \kappa_u$ . By the choice of  $\eta_\varepsilon$  and  $y$ , we have  $u \in \bigcup \{A_\rho^{*\varepsilon} \mid \rho < \kappa\}$ , and since  $q \in K_\varepsilon$  we have that  $u \in B^q$ .

Since  $B^q \subseteq B^r$ , we see that  $y \frown (u^\varepsilon, B^q)$  is a refinement of  $y \frown (u^\varepsilon, B^r)$ , and in particular  $y \frown (u^\varepsilon, B^q) \Vdash \zeta \dot{E}_\alpha^\varepsilon \zeta'$ . Since  $A^q = A^r$  and  $q$  is a condition, it follows from Clause (5) in Definition (4.5) that  $y \frown (u^\varepsilon, B^q) \Vdash \zeta \dot{E}_\beta^\varepsilon \zeta'$ .  $\blacktriangle 7.6$

**Definition 7.7.** Working in the model  $V[G][H_\xi][g^*]$ , we define for each  $\varepsilon \in S \cap \xi$  a relation  $\mathcal{E}^\varepsilon$  on the set  $\bigcup \{ \{b_\alpha \upharpoonright \zeta \mid \zeta < \kappa^+\} \times \kappa \mid \alpha < \chi^-\}$  by

$$z \mathcal{E}^\varepsilon z' \iff \exists \alpha < \chi^- z \mathcal{E}_\alpha^\varepsilon z'.$$

**Proposition 7.8.**  $V[G][H_\xi][g^*] \models \mathcal{E}^\varepsilon$  is of size  $\kappa^+$  and is universal for  $\{\mathcal{E}_\alpha^\varepsilon \mid \alpha < \chi^-\}$ .

*Proof.*  $\mathcal{E}^\varepsilon$  has size  $\kappa^+$  by the choice of  $\{b_\alpha \mid \alpha < \chi^-\}$ , as for  $\alpha < \chi^-$  and  $\zeta < \kappa^+$  we have that  $b_\alpha \upharpoonright \zeta \in \mathcal{T}$ , where  $\mathcal{T}$  is the  $\kappa^+$ -Kurepa tree added by  $\mathbb{Q}_0$ .

The universality follows from the definitions of  $\mathfrak{C}_\alpha^\varepsilon$ ,  $\mathcal{E}_\alpha^\varepsilon$  and  $\mathcal{E}^\varepsilon$ , and Lemma (7.6) which ensures that each  $f_\alpha^\varepsilon$  is an embedding of  $\mathfrak{C}_\alpha^\varepsilon$  into  $\mathcal{E}^\varepsilon$ .  $\blacktriangle 7.8$

**Proposition 7.9.** *In  $V[G][H_\xi][g^*]$  suppose  $\Xi (\in V[G][H_\xi][g^*])$  is cofinal in  $S \cap \xi$  and for all  $\varepsilon \in \Xi$  we have that  $\{\dot{E}_\alpha^\varepsilon \mid \alpha < \chi^-\}$  is a list of canonical names for all graphs on  $\kappa^+$ , Then  $\{\mathcal{E}^\varepsilon \mid \varepsilon \in \Xi\}$  is a universal family in the collection of graphs on  $\kappa^+$ .*

*Proof.* Let  $\mathfrak{G}$  be a graph on  $\kappa^+$  in  $V[G][H_\xi][g^*]$  and let  $\dot{E}$  be a canonical  $\mathbb{L} * \mathbb{P}_\xi * \mathbb{R}_v$ -name such that  $\mathfrak{G} = \dot{E}^{G * H_\xi * g^*}$ . As  $\text{cf}(\xi) > \kappa^+$  there is some  $\varepsilon \in \Xi$  such that  $\dot{E}$  is a  $\mathbb{L} * \mathbb{P}_\varepsilon * \mathbb{R}_{v^\varepsilon}$ -name and hence  $\mathfrak{G} = \dot{E}^{G * H_\varepsilon * g^\varepsilon}$ . By Proposition (7.8) we thus have that  $\mathfrak{G}$  embeds into  $\mathcal{E}^\varepsilon$ .  $\blacktriangle 7.9$

**Theorem 7.10.** *Suppose  $\kappa$  is a supercompact cardinal,  $\lambda < \kappa$  is a regular cardinal and  $\Theta$  is a cardinal with  $\text{cf}(\Theta) \geq \kappa^{++}$  and  $\kappa^{+3} \leq \Theta$ . There is a forcing extension in which cofinally many cardinals below  $\kappa$ ,  $\kappa$  itself and all cardinals greater than  $\kappa$  are preserved,  $\text{cf}(\kappa) = \lambda$ ,  $2^\kappa = 2^{\kappa^+} = \Theta$  and there is a universal family of graphs on  $\kappa^+$  of size  $\kappa^{++}$ .*

*Proof.* Let  $\chi = \Theta^+$ . It is standard that if  $\kappa$  is supercompact there is a forcing extension in which  $\kappa$  remains supercompact and GCH and  $\diamond_\chi(S_{\kappa^+}^\chi)$  hold. The conclusion is now immediate from Proposition (7.9).  $\blacktriangle 7.10$

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