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On regular reduced products*

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Abstract

Assume $\langle \aleph_0, \aleph_1 \rangle \rightarrow \langle \lambda, \lambda^+ \rangle$. Assume M is a model of a first order theory T of cardinality at most λ^+ in a vocabulary $\mathcal{L}(T)$ of cardinality $\leq \lambda$. Let N be a model with the same vocabulary. Let Δ be a set of first order formulas in $\mathcal{L}(T)$ and let D be a regular filter on λ . Then M is Δ -embeddable into the reduced power N^λ/D , provided that every Δ -existential formula true in M is true also in N . We obtain the following corollary: for M as above and D a regular ultrafilter over λ , M^λ/D is λ^{++} -universal. Our second result is as follows: For $i < \mu$ let M_i and N_i be elementarily equivalent models of a vocabulary which has cardinality $\leq \lambda$. Suppose D is a regular filter on μ and $\langle \aleph_0, \aleph_1 \rangle \rightarrow \langle \lambda, \lambda^+ \rangle$ holds. We show that then the second player has a winning strategy in the Ehrenfeucht-Fraïssé game of length λ^+ on $\prod_i M_i/D$ and $\prod_i N_i/D$. This yields the following corollary: Assume GCH and λ regular (or just $\langle \aleph_0, \aleph_1 \rangle \rightarrow \langle \lambda, \lambda^+ \rangle$ and $2^\lambda = \lambda^+$). For L , M_i and N_i be as above, if D is a regular filter on λ , then $\prod_i M_i/D \cong \prod_i N_i/D$.

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1 Introduction

Suppose M is a first order structure and F is the Frechet filter on ω . Then the reduced power M^ω/F is \aleph_1 -saturated and hence \aleph_2 -universal ([6]). This was generalized by Shelah in [10] to any filter F on ω for which B^ω/F is \aleph_1 -saturated, where B is the two element Boolean algebra, and in [8] to all regular filters on ω . In the first part of this paper we use the combinatorial principle $\square_\lambda^{b^*}$ of Shelah [11] to generalize the result from ω to arbitrary λ , assuming $\langle \aleph_0, \aleph_1 \rangle \rightarrow \langle \lambda, \lambda^+ \rangle$. This gives a partial solution to Conjecture 19 in [3]: if D is a regular ultrafilter over λ , then for all infinite M , the ultrapower M^λ/D is λ^{++} -universal.

The second part of this paper addresses Problem 18 in [3], which asks if it is true that if D is a regular ultrafilter over λ , then for all elementarily equivalent models M and N of cardinality $\leq \lambda$ in a vocabulary of cardinality $\leq \lambda$, the ultrapowers M^λ/D and N^λ/D are isomorphic. Keisler [7] proved this for good D assuming $2^\lambda = \lambda^+$. Benda [1] weakened "good" to "contains a good filter". We prove the claim in full generality, assuming $2^\lambda = \lambda^+$ and $\langle \aleph_0, \aleph_1 \rangle \rightarrow \langle \lambda, \lambda^+ \rangle$.

Regarding our assumption $\langle \aleph_0, \aleph_1 \rangle \rightarrow \langle \lambda, \lambda^+ \rangle$, by Chang's Two-Cardinal Theorem ([2]) $\langle \aleph_0, \aleph_1 \rangle \rightarrow \langle \lambda, \lambda^+ \rangle$ is a consequence of $\lambda = \lambda^{<\lambda}$. So our Theorem 2 settles Conjecture 19 of [3], and Theorem 13 settles Conjecture 18 of [3], under GCH for λ regular. For singular strong limit cardinals $\langle \aleph_0, \aleph_1 \rangle \rightarrow \langle \lambda, \lambda^+ \rangle$ follows from \square_λ (Jensen [5]). In the so-called Mitchell's model ([9]) $\langle \aleph_0, \aleph_1 \rangle \not\rightarrow \langle \aleph_1, \aleph_2 \rangle$, so our assumption is independent of ZFC.

2 Universality

Definition 1 Suppose Δ is a set of first order formulas of vocabulary L . The set of Δ -existential formulas is the set of formulas of the form

$$\exists x_1 \dots \exists x_n (\phi_1 \wedge \dots \wedge \phi_n),$$

where each ϕ_i is in Δ . The set of weakly Δ -existential formulas is the set of formulas of the above form, where each ϕ_i is in Δ or is the negation of a formula in Δ . If M and N are L -structures and $h : M \rightarrow N$, we say that h is a Δ -homomorphism if h preserves the truth of Δ -formulas. If h preserves also the truth of negations of Δ -formulas, it is called a Δ -embedding.

Theorem 2 Assume $\langle \aleph_0, \aleph_1 \rangle \rightarrow \langle \lambda, \lambda^+ \rangle$. Let M be a model of a first order theory T of cardinality at most λ^+ , in a language L of cardinality $\leq \lambda$ and let N be a model with the same vocabulary. Let Δ be a set of first order formulas in L and let D be a regular filter on λ . We assume that every weakly Δ -existential sentence true in M is true also in N . Then there is a Δ -embedding of M into the reduced power N^λ/D .

By letting Δ be the set of all first order sentences, we get from Theorem 2 and Łoś' Lemma:

Corollary 3 Assume $\langle \aleph_0, \aleph_1 \rangle \rightarrow \langle \lambda, \lambda^+ \rangle$. If M is a model with vocabulary $\leq \lambda$, and D is a regular ultrafilter over λ , then M^λ/D is λ^{++} -universal, i.e. if M' is of cardinality $\leq \lambda^+$, and $M' \equiv M$, then M' is elementarily embeddable into the ultrapower M^λ/D .

We can replace "weakly Δ -existential" by " Δ -existential" in the Theorem, if we only want a Δ -homomorphism.

The proof of Theorem 2 is an induction over λ and λ^+ respectively, as follows. Suppose $M = \{a_\zeta : \zeta < \lambda^+\}$. We associate to each $\zeta < \lambda^+$ finite sets u_i^ζ , $i < \lambda$, and represent the formula set Δ as a union of finite sets Δ_i . At stage i , for each $\zeta < \lambda^+$ we consider the Δ_i -type of the elements a_ζ of the model whose indices lie in the set u_i^ζ , $\zeta < \lambda^+$. This will yield a witness $f_\zeta(i)$ in N at stage i, ζ . Our embedding is then given by $a_\zeta \mapsto \langle f_\zeta(i) : i < \lambda \rangle / D$.

We need first an important lemma, reminiscent of Proposition 5.1 in [11]:

Lemma 4 Assume $\langle \aleph_0, \aleph_1 \rangle \rightarrow \langle \lambda, \lambda^+ \rangle$. Let D be a regular filter on λ . There exist sets u_i^ζ and integers n_i for each $\zeta < \lambda^+$ and $i < \lambda$ such that for each i, ζ

- (i) $|u_i^\zeta| < n_i < \omega$
- (ii) $u_i^\zeta \subseteq \zeta$
- (iii) Let B be a finite set of ordinals and let ζ be such that $B \subseteq \zeta < \lambda^+$. Then $\{i : B \subseteq u_i^\zeta\} \in D$
- (iv) Coherency: $\gamma \in u_i^\zeta \Rightarrow u_i^\gamma = u_i^\zeta \cap \gamma$

Assuming the lemma, and letting $M = \{a_\zeta : \zeta < \lambda^+\}$ we now define, for each ζ , a function $f_\zeta : \lambda \mapsto N$.

Let $\Delta = \{\phi_\alpha : \alpha < \lambda\}$ and let $\{A_\alpha : \alpha < \lambda\}$ be a family witnessing the regularity of D. Thus for each i , the set $w_i = \{\alpha : i \in A_\alpha\}$ is finite. Let $\Delta_i = \{\phi_\alpha : \alpha \in w_i\}$, and let u_i^ζ, n_i be as in the lemma.

We define a sequence of formulas essential to the proof: suppose $\zeta < \lambda^+$ and $i < \lambda$. Let $m_i^\zeta = |u_i^\zeta|$ and let

$$u_i^\zeta = \{\xi_{\zeta,i,0}, \dots, \xi_{\zeta,i,m_i^\zeta-1}\}$$

be an increasing enumeration of u_i^ζ . (We adopt henceforth the convention that any enumeration of u_i^ζ that is given is an increasing enumeration.) Let $\bar{\theta}_i^\zeta$ be the Δ_i -type of the tuple $\langle a_{\xi_{\zeta,i,0}}, \dots, a_{\xi_{\zeta,i,m_i^\zeta-1}}, a_\zeta \rangle$ in M . (So every $\phi(x_{\xi_{\zeta,i,0}}, \dots, x_{\xi_{\zeta,i,m_i^\zeta-1}}, x_\zeta) \in \Delta_i$ or its negation occurs as a conjunct of $\bar{\theta}_i^\zeta$, according to whether $\phi(a_{\xi_{\zeta,i,0}}, \dots, a_{\xi_{\zeta,i,m_i^\zeta-1}}, a_\zeta)$ or $\neg\phi(a_{\xi_{\zeta,i,0}}, \dots, a_{\xi_{\zeta,i,m_i^\zeta-1}}, a_\zeta)$ holds in M .) We define the formula θ_i^ζ for each i by downward induction on m_i^ζ as follows:

Case 1: $m_i^\zeta = n_i$. Let $\theta_i^\zeta = \bigwedge \bar{\theta}_i^\zeta$.

Case 2: $m_i^\zeta < n_i$. Let θ_i^ζ be the conjunction of $\bar{\theta}_i^\zeta$ and all formulas of the form $\exists x_{m_i^\zeta} \theta_i^\epsilon(x_0, \dots, x_{m_i^\zeta-1}, x_{m_i^\zeta})$, where ϵ satisfies $u_i^\epsilon = u_i^\zeta \cup \{\zeta\}$ and hence $m_i^\epsilon = m_i^\zeta + 1$.

An easy induction shows that for a fixed $i < \lambda$, the cardinality of the set $\{\theta_i^\zeta : \zeta < \lambda^+\}$ is finite, using n_i .

Let $i < \lambda$ be fixed. We define $f_\zeta(i)$ by induction on $\zeta < \lambda^+$ in such a way that the following condition remains valid:

(IH) If $\zeta^* < \zeta$ and $u_i^{\zeta^*} = \{r_{\epsilon_1}, \dots, r_{\epsilon_k}\}$, then $N \models \theta_i^{\zeta^*}(f_{\epsilon_1}(i), \dots, f_{\epsilon_k}(i), f_{\zeta^*}(i))$.

To define $f_\zeta(i)$, we consider different cases:

Case 1: $n_i = m_i^\zeta$.

Case 1.1: $n_i = 0$. Then θ_i^ζ is the Δ_i type of the element a_ζ . But then

$$\begin{aligned} M &\models \theta_i^\zeta(a_\zeta) \Rightarrow \\ M &\models \exists x_0 \theta_i^\zeta(x_0) \Rightarrow \\ N &\models \exists x_0 \theta_i^\zeta(x_0), \end{aligned}$$

where the last implication follows from the assumption that N satisfies the weakly Δ -existential formulas holding in M . Now choose an element $b \in N$ to witness this formula and set $f_\zeta(i) = b$.

Case 1.2: $n_i > 0$. Let $u_i^\zeta = \{\xi_1, \dots, \xi_{m_i^\zeta}\}$. Since $m_i^\zeta = n_i$, the formula θ_i^ζ is the Δ_i -type of the elements $\{\xi_1, \dots, \xi_{m_i^\zeta}\}$. By assumption $\gamma = \xi_{m_i^\zeta}$ is the maximum element of u_i^ζ . Thus by coherency, $u_i^\gamma = u_i^\zeta \cap \gamma = \{\xi_1, \dots, \xi_{m_i^\zeta-1}\}$. Since $\gamma < \zeta$, we know by the induction hypothesis that

$$N \models \theta_i^\gamma(f_{\xi_1}(i), \dots, f_{\xi_{m_i^\zeta}}(i)).$$

By the formula construction θ_i^γ contains the formula $\exists x_{m_i^\zeta} \theta_i^\zeta(x_1, \dots, x_{m_i^\zeta})$, since $u_i^\zeta = u_i^\gamma \cup \{\gamma\}$ and since $m_i^\gamma < n_i$. Thus

$$N \models \exists x_{m_i^\zeta+1} \theta_i^\zeta(f_{\xi_1}(i), \dots, f_{\xi_{m_i^\zeta}}(i), x_{m_i^\zeta+1}).$$

As before choose an element $b \in N$ to witness this formula and set $f_\zeta(i) = b$.

Case 2: $m_i^\zeta < n_i$. Let $u_i^\zeta = \{\xi_1, \dots, \xi_{m_i^\zeta}\}$. We have that $M \models \theta_i^\zeta(a_{\xi_1}, \dots, a_{\xi_{m_i^\zeta}}, a_\zeta)$,

and therefore $M \models \exists x_{m_i^\zeta+1} \theta_i^\zeta(a_{\xi_1}, \dots, a_{\xi_{m_i^\zeta}}, x_{m_i^\zeta+1})$. Let $\gamma = \max(u_i^\zeta) = \xi_{m_i^\zeta}$.

By coherency, $u_i^\gamma = u_i^\zeta \cap \gamma$ and therefore since $\gamma < \zeta$ by the induction hypothesis we have that

$$N \models \theta_i^\gamma(f_{\xi_1}(i), \dots, f_{\xi_{m_i^\zeta-1}}(i), f_\gamma(i)).$$

But then as in case 1.2 we can infer that

$$N \models \exists x_{m_i^\zeta+1} \theta_i^\zeta(f_{\xi_1}(i), \dots, f_{\xi_{m_i^\zeta}}(i), x_{m_i^\zeta+1}).$$

As in case 1 choose an element $b \in N$ to witness this formula and set $f_\zeta(i) = b$.

It remains to be shown that the mapping $a_\zeta \mapsto \langle f_\zeta(i) : i < \lambda \rangle / D$ satisfies the requirements of the theorem, i.e. we must show, for all ϕ which is in Δ , or whose negation is in Δ ,

$$M \models \phi(a_{\xi_1}, \dots, a_{\xi_k}) \Rightarrow \{i : N \models \phi(f_{\xi_1}(i), \dots, f_{\xi_k}(i))\} \in D.$$

So let such a ϕ be given, and suppose $M \models \phi(a_{\xi_1}, \dots, a_{\xi_k})$. Let $I_\phi = \{i : N \models \phi(f_{\xi_1}(i), \dots, f_{\xi_k}(i))\}$. We wish to show that $I_\phi \in D$. Let $\alpha < \lambda$ so that

ϕ is ϕ_α or its negation. It suffices to show that $A_\alpha \subseteq I_\phi$. Let $\zeta < \lambda^+$ be such that $\{\xi_1, \dots, \xi_n\} \subseteq \zeta$. By Lemma 4 condition (iii), $\{i : \{\xi_1, \dots, \xi_n\} \subseteq u_i^\zeta\} \in D$. So it suffices to show

$$A_\alpha \cap \{i : \{\xi_1, \dots, \xi_n\} \subseteq u_i^\zeta\} \subseteq I_\phi.$$

Let $i \in A_\alpha$ such that $\{\xi_1, \dots, \xi_n\} \subseteq u_i^\zeta$. By the definition of θ_i^ζ we know that $N \models \theta_i^\zeta(f_{\xi_1}(i), \dots, f_{\xi_k}(i))$. But the Δ_i -type of the tuple $\langle \xi_1, \dots, \xi_k \rangle$ occurs as a conjunct of θ_i^ζ , and therefore $N \models \phi(f_{\xi_1}(i), \dots, f_{\xi_k}(i))$ \square

3 Proof of Lemma 4

We now prove Lemma 4. We first prove a weaker version in which the filter is not given in advance:

Lemma 5 *Assume $\langle \aleph_0, \aleph_1 \rangle \rightarrow \langle \lambda, \lambda^+ \rangle$. There exist sets $\langle u_i^\zeta : \zeta < \lambda^+, i < \text{cof}(\lambda) \rangle$, integers n_i and a regular filter D on λ , generated by λ sets, such that (i)-(iv) of Lemma 4 hold.*

Proof. By [11, Proposition 5.1, p. 149] the assumption $\langle \aleph_0, \aleph_1 \rangle \rightarrow \langle \lambda, \lambda^+ \rangle$ is equivalent to:

$\square_\lambda^{b^*}$: There is a λ^+ -like linear order L , sets $\langle C_a^\zeta : a \in L, \zeta < \text{cof}(\lambda) \rangle$, equivalence relations $\langle E^\zeta : \zeta < \text{cof}(\lambda) \rangle$, and functions $\langle f_{a,b}^\zeta : \zeta < \lambda, a \in L, b \in L \rangle$ such that

- (i) $\bigcup_\zeta C_a^\zeta = \{b : b <_L a\}$ (an increasing union in ζ).
- (ii) If $b \in C_a^\zeta$, then $C_b^\zeta = \{c \in C_a^\zeta : c <_L b\}$.
- (iii) E^ζ is an equivalence relation on L with $\leq \lambda$ equivalence classes.
- (iv) If $\zeta < \xi < \text{cof}(\lambda)$, then E^ξ refines E^ζ .
- (v) If $aE^\zeta b$, then $f_{a,b}^\zeta$ is an order-preserving one to one mapping from C_a^ζ onto C_b^ζ such that for $d \in C_a^\zeta$, $dE^\zeta f_{a,b}^\zeta(d)$.
- (vi) If $\zeta < \xi < \text{cof}(\lambda)$ and $aE^\xi b$, then $f_{a,b}^\zeta \subseteq f_{a,b}^\xi$.
- (vii) If $f_{a,b}^\zeta(a_1) = b_1$, then $f_{a_1,b_1}^\zeta \subseteq f_{a,b}^\zeta$.
- (viii) If $a \in C_b^\zeta$ then $\neg E^\zeta(a, b)$.

This is not quite enough to prove Lemma 5, so we have to work a little more. Let

$$\Xi_\zeta = \{a/E^\zeta : a \in L\}.$$

We assume, for simplicity, that $\zeta \neq \xi$ implies $\Xi_\zeta \cap \Xi_\xi = \emptyset$. Define for $t_1, t_2 \in \Xi_\zeta$:

$$t_1 <_\zeta t_2 \iff (\exists a_1 \in t_1)(\exists a_2 \in t_2)(a_1 \in C_{a_2}^\zeta).$$

Proposition 6 $\langle \Xi_\zeta, <_\zeta \rangle$ is a tree order with $cf(\lambda)$ as the set of levels.

Proof. We need to show (a) $t_1 <_\zeta t_2 <_\zeta t_3$ implies $t_1 <_\zeta t_3$, and (b) $t_1 <_\zeta t_3$ and $t_2 <_\zeta t_3$ implies $t_1 <_\zeta t_2$ or $t_2 <_\zeta t_1$ or $t_1 = t_2$. For the first, $t_1 <_\zeta t_2$ implies there exists $a_1 \in t_1$ and $a_2 \in t_2$ such that $a_1 \in C_{a_2}^\zeta$. Similarly $t_2 <_\zeta t_3$ implies there exists $b_2 \in t_2$ and $b_3 \in t_3$ such that $b_2 \in C_{b_3}^\zeta$. Now $a_2 E^\zeta b_2$ and hence we have the order preserving map f_{a_2, b_2}^ζ from $C_{a_2}^\zeta$ onto $C_{b_2}^\zeta$. Recalling $a_1 \in C_{a_2}^\zeta$, let $f_{a_2, b_2}^\zeta(a_1) = b_1$. Then by (vi), $a_1 E^\zeta b_1$ and hence $b_1 \in t_1$. But then $b_1 \in C_{b_2}^\zeta$ implies $b_1 \in C_{b_3}^\zeta$, by coherence and the fact that $b_2 \in C_{b_3}^\zeta$. But then it follows that $t_1 <_\zeta t_3$.

Now assume $t_1 <_\zeta t_3$ and $t_2 <_\zeta t_3$. Let $a_1 \in t_1$ and $a_3 \in t_3$ be such that $a_1 \in C_{a_3}^\zeta$, and similarly let b_2 and b_3 be such that $b_2 \in C_{b_3}^\zeta$. $a_3 E^\zeta b_3$ implies we have the order preserving map f_{a_3, b_3}^ζ from $C_{a_3}^\zeta$ to $C_{b_3}^\zeta$. Letting $f_{a_3, b_3}^\zeta(a_1) = b_1$, we see that $b_1 \in C_{b_3}^\zeta$. If $b_1 <_L b_2$, then we have $C_{b_2}^\zeta = C_{b_3}^\zeta \cap \{c \mid c < b_2\}$ which implies $b_1 \in C_{b_2}^\zeta$, since, as f_{a_3, b_3}^ζ is order preserving, $b_1 <_L b_2$. Thus $t_1 <_\zeta t_2$. The case $b_2 <_L b_1$ is proved similarly, and $b_1 = b_2$ is trivial. \square

For $a <_L b$ let

$$\xi(a, b) = \min\{\zeta : a \in C_b^\zeta\}.$$

Denoting $\xi(a, b)$ by ξ , let

$$tp(a, b) = \langle a/E^\xi, b/E^\xi \rangle.$$

If $a_1 <_L \dots <_L a_n$, let

$$tp(\langle a_1, \dots, a_n \rangle) = \{\langle l, m, tp(a_l, a_m) \rangle \mid 1 \leq l < m \leq n\}$$

and

$$\Gamma = \{tp(\vec{a}) : \vec{a} \in {}^{<\omega}L\}.$$

For $t = tp(\vec{a})$, $\vec{a} \in {}^n L$ we use n_t to denote the length of \vec{a} .

Proposition 7 *If $a_0 <_L \dots <_L a_n$, then*

$$\max\{\xi(a_l, a_m) : 0 \leq l < m \leq n\} = \max\{\xi(a_l, a_n) : 0 \leq l < n\}.$$

Proof. Clearly the right hand side is \leq the left hand side. To show the left hand side is \leq the right hand side, let $l < m < n$ be arbitrary. If $\xi(a_l, a_n) \leq \xi(a_m, a_n)$, then $\xi(a_l, a_m) \leq \xi(a_m, a_n)$. On the other hand, if $\xi(a_l, a_n) > \xi(a_m, a_n)$, then $\xi(a_l, a_m) \leq \xi(a_l, a_n)$. In either case $\xi(a_l, a_m) \leq \max\{\xi(a_k, a_n) : 0 \leq k < n\}$. \square

Let us denote $\max\{\xi(a_l, a_n) : 0 \leq l < n\}$ by $\xi(\vec{a})$. We define on Γ a two-place relation \leq_Γ as follows:

$$t_1 <_\Gamma t_2$$

if there exists a tuple $\langle a_0, \dots, a_{n_{t_2}-1} \rangle$ realizing t_2 such that some subsequence of the tuple realizes t_1 .

Clearly, $\langle \Gamma, \leq_\Gamma \rangle$ is a directed partial order.

Proposition 8 *For $t \in \Gamma$, $t = tp(b_0, \dots, b_{n-1})$ and $a \in L$, there exists at most one $k < n$ such that $b_k E^{\xi(b_0, \dots, b_{n-1})} a$.*

Proof. Let $\zeta = \xi(b_0, \dots, b_{n-1})$ and let $b_{k_1} \neq b_{k_2}$ be such that $b_{k_1} E^\zeta a$ and $b_{k_2} E^\zeta a$, $k_1, k_2 \leq n-1$. Without loss of generality, assume $b_{k_1} < b_{k_2}$. Since E^ζ is an equivalence relation, $b_{k_2} E^\zeta b_{k_1}$ and thus we have an order preserving map $f_{b_{k_2}, b_{k_1}}^\zeta$ from $C_{b_{k_2}}^\zeta$ to $C_{b_{k_1}}^\zeta$. Also $b_{k_1} \in C_{b_{k_2}}^\zeta$, by the definition of ζ and by coherence, and therefore $f_{b_{k_2}, b_{k_1}}^\zeta(b_{k_1}) E^\zeta b_{k_1}$. But this contradicts (viii), since $f_{b_{k_2}, b_{k_1}}^\zeta(b_{k_1}) \in C_{b_{k_1}}^\zeta$. \square

Definition 9 *For $t \in \Gamma$, $t = tp(b_0, \dots, b_{n-1})$ and $a \in L$ suppose there exists $k < n$ such that $b_k E^{\xi(b_0, \dots, b_{n-1})} a$. Then let $u_t^a = \{f_{a, b_k}^{\xi(b_0, \dots, b_{n-1})}(b_l) : l < k\}$ Otherwise, let $u_t^a = \emptyset$.*

Finally, let D be the filter on Γ generated by the λ sets

$$\Gamma_{\geq t^*} = \{t \in \Gamma : t^* <_L t\}.$$

We can now see that the sets u_t^a , the numbers n_t and the filter D satisfy conditions (i)-(iv) of Lemma 4 with L instead of λ^+ : Conditions (i) and (ii)

are trivial in this case. Condition (iii) is verified as follows: Suppose B is finite. Let $a \in L$ be such that $(\forall x \in B)(x <_L a)$. Let \vec{a} enumerate $B \cup \{a\}$ in increasing order and let $t^* = \text{otp}(\vec{a})$. Clearly

$$t \in \Gamma_{\geq t^*} \Rightarrow B \subseteq u_t^a.$$

Condition (iv) follows directly from Definition 9 and Proposition 8.

To get the Lemma on λ^+ we observe that since L is λ^+ -like, we can assume that $\langle \lambda^+, < \rangle$ is a submodel of $\langle L, <_L \rangle$. Then we define $v_t^\alpha = u_t^\alpha \cap \{\beta : \beta < \alpha\}$. Conditions (i)-(iv) of Lemma 5 are still satisfied. Also having D a filter of Γ instead of λ is immaterial as $|\Gamma| = \lambda$. \square

Now back to the proof of Lemma 4. Suppose u_i^ζ, n_i and D are as in Lemma 5, and suppose D' is an arbitrary regular filter on λ . Let $\{A_\alpha : \alpha < \lambda\}$ be a family of sets witnessing the regularity of D' , and let $\{Z_\alpha : \alpha < \lambda\}$ be the family generating D . We define a function $h : \lambda \rightarrow \lambda$ as follows. Suppose $i < \lambda$. Then let

$$h(i) \in \bigcap \{Z_\alpha \mid i \in A_\alpha\}.$$

Now define $v_\alpha^\zeta = u_{h(\alpha)}^\zeta$. Define also $n_\alpha = n_{h(\alpha)}$. Now the sets v_α^ζ and the numbers n_α satisfy the conditions of Lemma 4. \square

4 Is $\square_\lambda^{b^*}$ needed for Lemma 5?

In this section we show that the conclusion of Lemma 5 (and hence of Lemma 4) implies $\square_\lambda^{b^*}$ for singular strong limit λ . By [11, Theorem 2.3 and Remark 2.5], $\square_\lambda^{b^*}$ is equivalent, for singular strong limit λ , to the following principle:

\mathcal{S}_λ : There are sets $\langle C_a^i : a < \lambda^+, i < \text{cf}(\lambda) \rangle$ such that

- (i) If $i < j$, then $C_a^i \subseteq C_a^j$.
- (ii) $\bigcup_i C_a^i = a$.
- (iii) If $b \in C_a^i$, then $C_b^i = C_a^i \cap b$.
- (iv) $\sup\{\text{otp}(C_a^i) : a < \lambda^+\} < \lambda$.

Thus it suffices to prove:

Proposition 10 *Suppose the sets u_i^ζ and the filter D are as given by Lemma 5 and λ is a limit cardinal. Then \mathcal{S}_λ holds.*

Proof. Suppose $\mathcal{A} = \{A_\alpha : \alpha < \lambda\}$ is a family of sets generating D . W.l.o.g., \mathcal{A} is closed under finite intersections. Let λ be the union of the increasing sequence $\langle \lambda_\alpha : \alpha < cf(\lambda) \rangle$, where $\lambda_0 \geq \omega$. Let the sequence $\langle \Gamma_\alpha : \alpha < cf(\lambda) \rangle$ satisfy:

- (a) $|\Gamma_\alpha| \leq \lambda_\alpha$
- (b) Γ_α is continuously increasing in α with λ as union
- (c) If $\beta_1, \dots, \beta_n \in \Gamma_\alpha$, then there is $\gamma \in \Gamma_\alpha$ such that

$$A_\gamma = A_{\beta_1} \cap \dots \cap A_{\beta_n}.$$

The sequence $\langle \Gamma_\alpha : \alpha < cf(\lambda) \rangle$ enables us to define a sequence that will witness \mathcal{S}_λ . For $\alpha < cf(\lambda)$ and $\zeta < \lambda^+$, let

$$V_\zeta^\alpha = \{\xi < \zeta : (\exists \gamma \in \Gamma_\alpha)(A_\gamma \subseteq \{i : \xi \in u_i^\zeta\})\}.$$

Lemma 11 (1) $\langle V_\zeta^\alpha : \alpha < \lambda \rangle$ is a continuously increasing sequence of subsets of ζ , $|V_\zeta^\alpha| \leq \lambda_\alpha$, and $\bigcup \{V_\zeta^\alpha : \alpha < cf(\lambda)\} = \zeta$.

(2) If $\xi \in V_\zeta^\alpha$, then $V_\xi^\alpha = V_\zeta^\alpha \cap \xi$.

Proof. (1) is a direct consequence of the definitions. (2) follows from the respective property of the sets u_i^ζ . \square

Lemma 12 $\sup\{otp(V_\zeta^\alpha) : \zeta < \lambda^+\} \leq \lambda_\alpha^+$.

Proof. By the previous Lemma, $|V_\zeta^\alpha| \leq \lambda_\alpha$. Therefore $otp(V_\zeta^\alpha) < \lambda_\alpha^+$ and the claim follows. \square

The proof of the proposition is complete: (i)-(iii) follows from Lemma 11, (iv) follows from Lemma 12 and the assumption that λ is a limit cardinal. \square

More equivalent conditions for the case λ singular strong limit, D a regular ultrafilter on λ , are under preparation.

5 Ehrenfeucht-Fraïssé-games

Let M and N be two first order structures of the same vocabulary L . All vocabularies are assumed to be relational. The *Ehrenfeucht-Fraïssé-game of length γ of M and N* denoted by EFG_γ is defined as follows: There are two players called I and II. First I plays x_0 and then II plays y_0 . After this I plays x_1 , and II plays y_1 , and so on. If $\langle (x_\beta, y_\beta) : \beta < \alpha \rangle$ has been played and $\alpha < \gamma$, then I plays x_α after which II plays y_α . Eventually a sequence $\langle (x_\beta, y_\beta) : \beta < \gamma \rangle$ has been played. The rules of the game say that both players have to play elements of $M \cup N$. Moreover, if I plays his x_β in M (N), then II has to play his y_β in N (M). Thus the sequence $\langle (x_\beta, y_\beta) : \beta < \gamma \rangle$ determines a relation $\pi \subseteq M \times N$. Player II wins this round of the game if π is a partial isomorphism. Otherwise I wins. The notion of winning strategy is defined in the usual manner. We say that a player *wins* EFG_γ if he has a winning strategy in EFG_γ .

Note that if II has a winning strategy in EFG_γ on M and N , where M and N are of size $\leq |\gamma|$, then $M \cong N$.

Assume L is of cardinality $\leq \lambda$ and for each $i < \lambda$ let M_i and N_i are elementarily equivalent L -structures. Shelah proved in [12] that if D is a regular filter on λ , then Player II has a winning strategy in the game EFG_γ on $\prod_i M_i/D$ and $\prod_i N_i/D$ for each $\gamma < \lambda^+$. We show that under a stronger assumption, II has a winning strategy even in the game EFG_{λ^+} . This makes a big difference because, assuming the models M_i and N_i are of size $\leq \lambda^+$, $2^\lambda = \lambda^+$, and the models $\prod_i M_i/D$ and $\prod_i N_i/D$ are of size $\leq \lambda^+$. Then by the remark above, if II has a winning strategy in EFG_{λ^+} , the reduced powers are actually isomorphic. Hyttinen [4] proved this under the assumption that the filter is, in his terminology, semigood.

Theorem 13 *Assume $\langle \aleph_0, \aleph_1 \rangle \rightarrow \langle \lambda, \lambda^+ \rangle$. Let L be a vocabulary of cardinality $\leq \lambda$ and for each $i < \lambda$ let M_i and N_i be two elementarily equivalent L -structures. If D is a regular filter on λ , then Player II has a winning strategy in the game EFG_{λ^+} on $\prod_i M_i/D$ and $\prod_i N_i/D$.*

Proof. We use Lemma 4. If $i < \lambda$, then, since M_i and N_i are elementarily equivalent, Player II has a winning strategy σ_i in the game EFG_{n_i} on M_i and N_i . We will use the set u_i^ζ to put these short winning strategies together into one long winning strategy.

A “good” position is a sequence $\langle (f_\zeta, g_\zeta) : \zeta < \xi \rangle$, where $\xi < \lambda^+$, and for all $\zeta < \xi$ we have $f_\zeta \in \prod_i M_i$, $g_\zeta \in \prod_i N_i$, and if $i < \lambda$, then $\langle (f_\epsilon(i), g_\epsilon(i)) : \epsilon \in u_i^\zeta \cup \{\zeta\} \rangle$ is a play according to σ_i .

Note that in a good position the equivalence classes of the functions f_ζ and g_ζ determine a partial isomorphism of the reduced products. The strategy of player II is to keep the position of the game “good”, and thereby win the game. Suppose ξ rounds have been played and II has been able to keep the position “good”. Then player I plays f_ξ . We show that player II can play g_ξ so that $\langle (f_\zeta, g_\zeta) : \zeta \leq \xi \rangle$ remains “good”. Let $i < \lambda$. Let us look at $\langle (f_\epsilon(i), g_\epsilon(i)) : \epsilon \in u_i^\xi \rangle$. We know that this is a play according to the strategy σ_i and $|u_i^\xi| < n_i$. Thus we can play one more move in EF_{n_i} on M_i and N_i with player I playing $f_\xi(i)$. Let $g_\xi(i)$ be the answer of II in this game according to σ_i . The values $g_\xi(i)$, $i < \lambda$, constitute the function g_ξ . We have showed that II can maintain a “good” position. \square

Corollary 14 *Assume GCH and λ regular (or just $\langle \aleph_0, \aleph_1 \rangle \rightarrow \langle \lambda, \lambda^+ \rangle$ and $2^\lambda = \lambda^+$). Let L be a vocabulary of cardinality $\leq \lambda$ and for each $i < \lambda$ let M_i and N_i be two elementarily equivalent L -structures. If D is a regular filter on λ , then $\prod_i M_i/D \cong \prod_i N_i/D$.*

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