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There May Be No Nowhere Dense Ultrafilter

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Abstract. We show the consistency of $ZFC +$ "there is no NWD-ultrafilter on ω ", which means: for every non-principal ultrafilter \mathcal{D} on the set of natural numbers, there is a function f from the set of natural numbers to the reals, such that for every nowhere dense set A of reals, $\{n : f(n) \in A\} \notin \mathcal{D}$. This answers a question of van Douwen, which was put in more general context by Baumgartner.

0 Introduction

We prove here the consistency of "there is no NWD-ultrafilter on ω " (non-principal, of course). This answers a question of van Douwen [vD81] which appears as question 31 of [B6]. Baumgartner [B6] considers the question which he dealt more generally with J -ultrafilter where

- Definition 1.**
1. An ultrafilter \mathcal{D} , say on ω , is called a J -ultrafilter where J is an ideal on some set X (to which all singletons belong, to avoid trivialities) if for every function $f : \omega \rightarrow X$ for some $A \in \mathcal{D}$ we have $f''(A) \in J$.
 2. The NWD-ultrafilters are the J -ultrafilters for

$$J = \{B \subseteq \mathbb{Q} : B \text{ is nowhere dense}\}$$

(\mathbb{Q} is the set of all rationals; we will use an equivalent version, see 22).

This is also relevant for the consistency of "every (non-trivial) c.c.c. σ -centered forcing notion adds a Cohen real", see [Sh:F151].

The most natural approach to a proof of the consistency of "there is no NWD-ultrafilter" was to generalize the proof of CON(there is no P -point) (see [Sh:b, VI, §4] or [Sh:f, VI, §4]), but I (and probably others) have not seen how.

We use an idea taken from [Sh 407], which is to replace the given maximal ideal I on ω by a quotient; moreover, we allow ourselves to change the quotient.

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In fact, the forcing here is simpler than the one in [Sh 407]. A related work is Goldstern, Shelah [GoSh 388].

We similarly may consider the consistency of “no α -ultrafilter” for limit $\alpha < \omega_1$ (see [B6] for definition and discussion of α -ultrafilters). This question and the problems of preservation of ultrafilters and distinguishing existence properties of ultrafilters will be dealt with in a subsequent work [Sh:F187].

In §3 we note that any ultrafilter with property M (see Definition 25) is an NWD-ultrafilter, hence it is consistent that there is no ultrafilter (on ω) with property M .

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1 The basic forcing

In Definition 3 below we define the forcing notion $\mathbb{Q}_{I,h}^1$ which will be the one used in the proof of the main result 24. The other forcing notion defined below, $\mathbb{Q}_{I,h}^2$, is a relative of $\mathbb{Q}_{I,h}^1$. Various properties are much easier to check for $\mathbb{Q}_{I,h}^2$, but unfortunately it does not do the job. The reader interested in the main result of the paper only may concentrate on $\mathbb{Q}_{I,h}^1$.

Definition 2. Let I be an ideal on ω containing the family $[\omega]^{<\omega}$ of finite subsets of ω .

1. We say that an equivalence relation E is an I -equivalence relation if:

- (a) $\text{dom}(E) \subseteq \omega$,
- (b) $\omega \setminus \text{dom}(E) \in I$,
- (c) each E -equivalence class is in I .

2. For I -equivalence relations E_1, E_2 we write $E_1 \leq E_2$ if

- (i) $\text{dom}(E_2) \subseteq \text{dom}(E_1)$,
- (ii) $E_1 \upharpoonright \text{dom}(E_2)$ refines E_2 ,
- (iii) $\text{dom}(E_2)$ is the union of a family of E_1 -equivalence classes.

Definition 3. Let I be an ideal on ω to which all finite subsets of ω belong and let $h : \omega \rightarrow \omega$ be a non-decreasing function. Let $\ell \in \{1, 2\}$. We define a forcing notion $\mathbb{Q}_{I,h}^\ell$ (if $h(n) = n$ we may omit it) intended to add $\langle y_i^n : i < h(n), n < \omega \rangle$, $y_i^n \in \{-1, 1\}$. We use x_i^n as variables.

1. $p \in \mathbb{Q}_{I,h}^\ell$ if and only if $p = (H, E, A) = (H^p, E^p, A^p)$ and

- (a) E is an I -equivalence relation on $\text{dom}(E) \subseteq \omega$,
- (b) $A = \{n \in \text{dom}(E) : n = \min(n/E)\}$,
- (c) if $\ell = 1$, then H is a function with range $\subseteq \{-1, 1\}$ and domain

$$B_1^p = \{x_i^n : i < h(n) \text{ and } n \in \omega \setminus \text{dom}(E) \text{ or } n \in \text{dom}(E) \text{ and } i \in [h(\min(n/E)), h(n)]\},$$

(d) if $\ell = 2$, then

(α) H is a function on $\text{dom}(H) = B_2^p \cup B_3^p$, where

$$B_2^p = \{x_i^m : m \in \omega, A^p \cap (m+1) = \emptyset, i < h(m)\} \quad \text{and} \\ B_3^p = \{x_i^m : m \in \text{dom}(E^p) \setminus A^p \text{ or } m \notin \text{dom}(E^p) \text{ but } A^p \cap m \neq \emptyset, i < h(m)\},$$

(β) for $x_i^m \in B_3^p$, $H(x_i^m)$ is a function of the variables $\{x_j^n : (n, j) \in w_p(m, i)\}$ to $\{-1, 1\}$, where

$$w_p(m) = w_p(m, i) = \{(\ell, j) : \ell \in A^p \cap m \text{ and } j < h(\ell)\},$$

for $n \in A^p$ we stipulate $H^p(x_i^n) = x_i^n$ and

(γ) $H \upharpoonright B_2^p$ is a function to $\{-1, 1\}$.

(e) if $\ell = 2$ and $x_i^n \in B_3^p$, $n^* = \min(n/E^p) < n$ and $y_i^m \in \{-1, 1\}$ for $m \in A^p \cap n^*$, $i < h(m)$ and $z_j^n \in \{-1, 1\}$ for $j < h(n^*)$ then for some $y_j^{n^*} \in \{-1, 1\}$ for $j < h(n^*)$ we have

$$j < h(n^*) \Rightarrow z_j^n = (H^p(x_j^n))(\dots, y_i^m, \dots)_{(m,i) \in w_p(n,j)}.$$

When it can not cause any confusion, or we mean “for both $\ell = 1$ and $\ell = 2$ ”, we omit the superscript ℓ .

2. Defining functions like $H(x_i^m)$, $x_i^m \in B_3^p$ (when $\ell = 2$), we may allow to use dummy variables. In particular, if $H^p(x_i^m)$ is $-1, 1$ we identify it with constant functions with this value.

3. We say that a function $f : \{x_i^n : i < h(n), n < \omega\} \rightarrow \{-1, 1\}$ satisfies a condition $p \in \mathbb{Q}_{I,h}^\ell$ if:

- (a) $f(x_i^n) = H^p(x_i^n)$ when $x_i^n \in B_1^p$ and $\ell = 1$, or $x_i^n \in B_2^p$ and $\ell = 2$,
- (b) $f(x_i^n) = H^p(x_i^n)(\dots, f(x_j^m), \dots)_{(m,j) \in w_p(n,i)}$ when $\ell = 2$ and $x_i^n \in B_3^p$,
- (c) $f(x_i^n) = f(x_i^{\min(n/E^p)})$ when $\ell = 1$, $n \in \text{dom}(E^p)$ and $i < h(\min(n/E^p))$.

4. The partial order $\leq \leq \mathbb{Q}_{I,h}^\ell$ is defined by $p \leq q$ if and only if:

- (α) $E^p \leq E^q$,
- (β) every function $f : \{x_i^n : i < h(n), n < \omega\} \rightarrow \{-1, 1\}$ satisfying q satisfies p .

Proposition 4. $(\mathbb{Q}_{I,h}^\ell, \leq \mathbb{Q}_{I,h}^\ell)$ is a partial order. ■

Remark. We may reformulate the definition of the partial orders $\leq \mathbb{Q}_{I,h}^\ell$, making them perhaps more direct. Thus, in particular, if $p, q \in \mathbb{Q}_{I,h}^1$ then $p \leq \mathbb{Q}_{I,h}^1 q$ if and only if the demand (α) of 3(4) holds and

(β)^{*} for each $x_i^n \in B_1^q$:

- (i) if $x_i^n \in B_1^p$ then $H^q(x_i^n) = H^p(x_i^n)$,
- (ii) if $n \in \text{dom}(E^p) \setminus \text{dom}(E^q)$, $i < h(\min(n/E^p))$ then $H^q(x_i^n) = H^q(x_i^{\min(n/E^p)})$,

- (iii) if $n \in \text{dom}(E^q) \setminus A^p$, $\min(n/E^p) > \min(n/E^q)$ and $h(\min(n/E^q)) \leq i < h(\min(n/E^p))$ then $H^q(x_i^n) = H^q(x_i^{\min(n/E^p)})$.

The corresponding reformulation for the forcing notion $\mathbb{Q}_{I,h}^2$ is more complicated, but it should be clear too.

One may wonder why we have h in the definition of $\mathbb{Q}_{I,h}^\ell$ and we do not fix that e.g. $h(n) = n$. This is to be able to describe nicely what is the forcing notion $\mathbb{Q}_{I,h}^\ell$ below a condition p like. The point is that $\mathbb{Q}_{I,h}^\ell \upharpoonright \{q : q \geq p\}$ is like $\mathbb{Q}_{I,h}^\ell$ but we replace I by its quotient and we change the function h . More precisely:

Proposition 5. If $p \in \mathbb{Q}_{I,h}^\ell$ and $A^p = \{n_k : k < \omega\}$, $n_k < n_{k+1}$, $h^* : \omega \rightarrow \omega$ is $h^*(k) = h(n_k)$ and $I^* = \{B \subseteq \omega : \bigcup_{k \in B} (n_k/E) \in I\}$ then $\mathbb{Q}_{I,h}^\ell \upharpoonright \{q : p \leq \mathbb{Q}_{I,h}^\ell q\}$ is isomorphic to $\mathbb{Q}_{I^*,h^*}^\ell$.

PROOF Natural. ■

Definition 6. We define a $\mathbb{Q}_{I,h}$ -name $\bar{\eta} = \langle \eta_n : n < \omega \rangle$ by: η_n is a sequence of length $h(n)$ of members of $\{-1, 1\}$ such that

$$\eta_n[G_{\mathbb{Q}_{I,h}}](i) = 1 \iff (\exists p \in G_{\mathbb{Q}_{I,h}})(H^p(x_i^n) = 1).$$

[Note that in both cases $\ell = 1$ and $\ell = 2$, if $H^p(x_i^n) = 1$, $x_i^n \in \text{dom}(H^p)$ and $q \geq p$ then $H^q(x_i^n) = 1$; remember 3(2).]

Proposition 7.

1. If $n < \omega$, $A^p \cap (n+1) = \emptyset$ then $p \Vdash \langle \eta_n = \langle H^p(x_i^n) : i < h(n) \rangle \rangle$.
2. For each $n < \omega$ the set $\{p \in \mathbb{Q}_{I,h} : A^p \cap (n+1) = \emptyset\}$ is dense in $\mathbb{Q}_{I,h}$.
3. If $p \in \mathbb{Q}_{I,h}$ and $a \subseteq A^p$ is finite or at least $\bigcup_{n \in a} (n/E^p) \in I$, and

$$f : \{x_i^n : i < h(n) \text{ and } n \in a\} \rightarrow \{-1, 1\},$$

then for some unique q which we denote by $p^{[f]}$, we have:

- (a) $p \leq q \in \mathbb{Q}_{I,h}$,
- (b) $E^q = E^p \upharpoonright \bigcup \{n/E^p : n \in A \setminus a\}$,
- (c) for $n \in a$, $i < h(n)$ we have $H^q(x_i^n)$ is $f(x_i^n)$.

PROOF Straight. ■

Definition 8.

1. $p \leq_n q$ (in $\mathbb{Q}_{I,h}$) if $p \leq q$ and:

$$k \in A^p \ \& \ |A^p \cap k| < n \implies k \in A^q.$$

2. $p \leq_n^* q$ if $p \leq q$ and:

$$k \in A^p \ \& \ |A^p \cap k| < n \implies k \in A^q \ \& \ k/E^p = k/E^q.$$

3. $p \leq_n^\circ q$ if $p \leq_{n+1} q$ and:

$$n > 0 \implies p \leq_n^* q \quad \text{and} \quad \text{dom}(E^q) = \text{dom}(E^p).$$

4. For a finite set $\mathbf{u} \subseteq \omega$ we let $\text{var}(\mathbf{u}) \stackrel{\text{def}}{=} \{x_i^n : i < h(n), n \in \mathbf{u}\}$.

Proposition 9.

1. If $p \leq q$, \mathbf{u} is a finite initial segment of A^p and $A^q \cap \mathbf{u} = \emptyset$, then for some unique $f : \{x_i^n : i < h(n) \text{ and } n \in \mathbf{u}\} \rightarrow \{-1, 1\}$ we have $p \leq p^{[f]} \leq q$ (where $p^{[f]}$ is from 7(3)).
2. If $p \in \mathbb{Q}_{I,h}^\ell$ and \mathbf{u} is a finite initial segment of A^p then
 - (*)₁ $f \in \text{var}(\mathbf{u})\{-1, 1\}$ implies $p \leq p^{[f]}$ and

$$p^{[f]} \Vdash \langle (\forall n \in \mathbf{u})(\forall i < h(n))(\eta_n(i) = f(x_i^n)) \rangle,$$

(*)₂ the set $\{p^{[f]} : f \in \text{var}(\mathbf{u})\{-1, 1\}\}$ is predense above p (in $\mathbb{Q}_{I,h}^\ell$).

3. \leq_n is a partial order on $\mathbb{Q}_{I,h}^\ell$, and $p \leq_{n+1} q \implies p \leq_n q$. Similarly for $<_n^*$ and $<_n^\circ$. Also

$$p \leq_n^\circ q \implies p \leq_n^* q \implies p \leq_n q \implies p \leq q.$$

4. If $p \in \mathbb{Q}_{I,h}^\ell$, \mathbf{u} is a finite initial segment of A^p , $|\mathbf{u}| = n$ and

$$f : \{x_i^n : i < h(n) \text{ and } n \in \mathbf{u}\} \rightarrow \{-1, 1\} \quad \text{and} \quad p^{[f]} \leq q \in \mathbb{Q}_{I,h}^\ell,$$

then for some $r \in \mathbb{Q}_{I,h}^\ell$ we have $p \leq_n^* r \leq q$, $r^{[f]} = q$.

5. If $p \in \mathbb{Q}_{I,h}^2$, \mathbf{u} is a finite initial segment of A^p , $|\mathbf{u}| = n+1$ and

$$f : \{x_i^n : i < h(n) \text{ and } n \in \mathbf{u}\} \rightarrow \{-1, 1\} \quad \text{and} \quad p^{[f]} \leq q,$$

then for some $r \in \mathbb{Q}_{I,h}^2$ we have $p <_n^\circ r \leq q$ and $r^{[f]} = q$.

PROOF

- 1) Define $f : \{x_i^n : i < h(n) \text{ and } n \in \mathbf{u}\} \rightarrow \{-1, 1\}$ by:

$$f(x_i^n) \text{ is the constant value of } H^q(x_i^n)$$

(it is a constant function by 3(1)(e), 3(1)(f(γ))).

- 2) By 7 and 9(1).

- 3) Check.

- 4) First let us define the required condition r in the case $\ell = 1$. So we let

$$\text{dom}(E^r) = \bigcup_{n \in \mathbf{u}} (n/E^p) \cup \text{dom}(E^q),$$

$$E^r = \{(n_1, n_2) : n_1 E^q n_2 \text{ or for some } n \in \mathbf{u} \text{ we have: } \{n_1, n_2\} \subseteq (n/E^p)\},$$

$$A^r = \mathbf{u} \cup A^q$$

(note that if $n_1 E^q n_2$ then $n_1 \notin \mathbf{u}$). Next, for $x_i^n \in B_1^r$ (where B_1^r is given by 3(1)(e)) we define

$$H^r(x_i^n) = \begin{cases} H^q(x_i^n) & \text{if } n \notin \bigcup_{k \in \mathbf{u}} k/E^p \text{ and } x_i^n \in \text{dom}(H^q), \\ H^p(x_i^n) & \text{if } n \in \bigcup_{k \in \mathbf{u}} k/E^p \text{ and } x_i^n \in \text{dom}(H^p). \end{cases}$$

It should be clear that $r = (H^r, E^r, A^r) \in \mathbb{Q}_{I,h}^1$ is as required.

If $\ell = 2$ then we define r in a similar manner, but we have to be more careful defining the function H^r . Thus E^r and A^r are defined as above, B_2^r, B_3^r and $w_r(m, i)$ for $x_i^m \in B_3^r$ are given by 3(1)(f). Note that $B_2^r = B_2^p$ and $B_3^r \subseteq B_3^p$. Next we define:

- if $x_i^m \in B_2^r$ then $H^r(x_i^m) = H^p(x_i^m)$,
- if $x_i^m \in B_3^r, m \cap A^r \subseteq \mathbf{u}$ then $H^r(x_i^m) = H^p(x_i^m)$,
- if $x_i^m \in B_3^r$ and $\min(\text{dom}(E^q)) < m$ then

$$H^r(x_i^m)(\dots, x_j^k, \dots)_{(k,j) \in w_r(m,i)} = H^p(x_i^m)(x_j^k, H^q(x_j^{k'})_{(k',j') \in w_q(k',j')}}_{(k',j') \in w_p(m,i) \setminus w_r(m,i)}.$$

Note that if $(k', j') \in w_p(m, i) \setminus w_r(m, i)$, $x_i^m \in B_3^r$ then $k' \in A^p \setminus (\mathbf{u} \cup A^q)$ and $w_q(k', j') \subseteq w_r(m, i)$.

5) Like the proof of (4). Let $n^* = \max(\mathbf{u})$. Put $\text{dom}(E^r) = \text{dom}(E^p)$ and declare that $n_1 E^r n_2$ if one of the following occurs:

- (a) for some $n \in \mathbf{u} \setminus \{n^*\}$ we have $\{n_1, n_2\} \subseteq (n/E^p)$, or
- (b) $n_1 E^q n_2$ (so $n \in \mathbf{u} \Rightarrow \neg n E^p n_1$), or
- (c) $\{n_1, n_2\} \subseteq B$, where

$$B \stackrel{\text{def}}{=} n^*/E^p \cup \bigcup \{m/E^p : m \in \text{dom}(E^p) \setminus \text{dom}(E^q), \min(m/E^p) > n^*\}.$$

We let $A^r = \mathbf{u} \cup A^q$ (in fact A^r is defined from E^r). Finally the function H^r is defined exactly in the same manner as in (4) above (for $\ell = 2$). ■

Corollary 10. If $p \in \mathbb{Q}_{I,h}^\ell$, $n < \omega$ and τ is a $\mathbb{Q}_{I,h}^\ell$ -name of an ordinal, then there are \mathbf{u}, q and $\bar{\alpha} = \langle \alpha_f : f \in \text{var}(\mathbf{u}) \{-1, 1\} \rangle$ such that:

- (a) $p \leq_n^* q \in \mathbb{Q}_{I,h}^\ell$,
- (b) $\mathbf{u} = \{\ell \in A^p : |\ell \cap A^p| < n\}$,
- (c) for $f \in \text{var}(\mathbf{u}) \{-1, 1\}$ we have $q[f] \Vdash \tau = \alpha_f$,
- (d) $q \Vdash \tau \in \{\alpha_f : f \in \text{var}(\mathbf{u}) \{-1, 1\}\}$ (which is a finite set).

PROOF Let $k = \prod_{\ell \in \mathbf{u}} 2^{h(\ell)}$. Let $\{f_\ell : \ell < k\}$ enumerate $\text{var}(\mathbf{u}) \{-1, 1\}$. By induction on $\ell \leq k$ define r_ℓ, α_{f_ℓ} such that:

$$r_0 = p, \quad r_\ell \leq_n^* r_{\ell+1} \in \mathbb{Q}_{I,h}^\ell, \quad r_{\ell+1}^{[f_\ell]} \Vdash_{\mathbb{Q}_{I,h}^\ell} \tau = \alpha_{f_\ell}.$$

The induction step is by 9(4). Now $q = r_k$ and $\langle \alpha_f : f \in \text{var}(\mathbf{u}) \{-1, 1\} \rangle$ are as required. ■

Corollary 11. If $\ell = 2$ then in 10(a) we may require $p \leq_n^* q \in \mathbb{Q}_{I,h}^\ell$.

PROOF Similar: just use 9(5) instead of 9(4). ■

Definition 12. Let I be an ideal on ω containing $[\omega]^{<\omega}$ and let E be an I -equivalence relation.

1. We define a game $GM_I(E)$ between two players. The game lasts ω moves. In the n^{th} move the first player chooses an I -equivalence relation E_n^1 such that

$$E_0^1 = E, \quad [n > 0 \Rightarrow E_{n-1}^2 \leq E_n^1],$$

and the second player chooses an I -equivalence relation E_n^2 such that $E_n^1 \leq E_n^2$. In the end, the second player wins if

$$\bigcup \{\text{dom}(E_n^2) \setminus \text{dom}(E_{n+1}^1) : n \in \omega\} \in I$$

(otherwise the first player wins).

2. For a countable elementary submodel N of $(\mathcal{H}(\chi), \in, <^*)$ such that $I, E \in N$ we define a game $GM_I^N(E)$ in a similar manner as $GM_I(E)$, but we demand additionally that the relations played by both players are from N (i.e. $E_n^1, E_n^2 \in N$ for $n \in \omega$).

Proposition 13.

1. Assume that I is a maximal (non-principal) ideal on ω and E is an I -equivalence relation. Then the game $GM_I(E)$ is not determined. Moreover, for each countable $N \prec (\mathcal{H}(\chi), \in, <^*)$ such that $I, E \in N$ the game $GM_I^N(E)$ is not determined.
2. For the conclusion of (1) it is enough to assume that $\mathcal{P}(\omega)/I \models \text{ccc}$.

PROOF 1) As each player can imitate the other's strategy. ■

2) Easy, too, and will not be used in this paper. ■

Proposition 14.

1. Let $p \in \mathbb{Q}_{I,h}^\ell$. Suppose that the first player has no winning strategy in $GM_I(E^p)$. Then in the following game Player I has no winning strategy: in the n^{th} move,

Player I chooses a $\mathbb{Q}_{I,h}^\ell$ -name τ_n of an ordinal and

Player II chooses p_n, \mathbf{u}_n, w_n such that: w_n is a set of $\leq \prod_{\ell \in \mathbf{u}_n} 2^{h(\ell)}$ ordinals, $p \leq p_n \leq_n^* p_{n+1}$, $p_n \leq_{n+1} p_{n+1}$, \mathbf{u}_n a finite initial segment of A^{p_n}

with n elements and $p_n \Vdash \tau_n \in w_n$, moreover

$$f \in \text{var}(\mathbf{u}_n) \{-1, 1\} \Rightarrow p_n^{[f]} \text{ forces a value to } \tau_n.$$

In the end, the second player wins if for some $q \geq p$ we have

$$q \Vdash (\forall n \in \omega)(\tau_n \in w_n) \text{ " .}$$

We can let Player II choose $k_n < \omega$ and demand $|\mathbf{u}_n| \leq k_n$, and in the end Player II wins if $\liminf \langle k_n : n < \omega \rangle < \omega$ or there is q as above.

2. Let $p \in \mathbb{Q}_{I,h}^\ell$ and let N be a countable elementary submodel of $(\mathcal{H}(\chi), \in, <^*)$ such that $p, I, h \in N$. If the first player has no winning strategy in $GM_I^N(E^p)$ then Player I has no winning strategy in the game like above but with restriction that $\tau_n, p_n \in N$.

PROOF 1) As in [Sh 407, 1.11, p.436]. Let \mathbf{St}_p be a strategy for Player I in the game from 14. We shall define a strategy \mathbf{St} for the first player in $GM_I(E^p)$ during which the first player, on a side, plays a play of the game from 14, using \mathbf{St}_p , with $\langle p_\ell : \ell < \omega \rangle$ and he also chooses $\langle q_\ell : \ell < \omega \rangle$.

Then, as \mathbf{St} cannot be a winning strategy in $GM_I(E)$, in some play in which the first player uses his strategy \mathbf{St} he loses, and then $\langle p_\ell : \ell < \omega \rangle$ will have an upper bound as required.

In the n^{th} move (so $E_\ell^1, E_\ell^2, q_\ell, p_\ell, \mathbf{u}_\ell, w_\ell$ for $\ell < n$ are defined), the first player in addition to choosing E_n^1 chooses q_n, p_n, \mathbf{u}_n , such that:

- (a) $p = p_{-1} \leq q_0 = p_0, p_n \in \mathbb{Q}_{I,h}^\ell, q_n \in \mathbb{Q}_{I,h}^\ell$,
- (b) $p_n \leq_n^* p_{n+1} \in \mathbb{Q}_{I,h}^\ell$,
- (c) \mathbf{u}_0 is \emptyset ,
- (d) $\mathbf{u}_{n+1} = \mathbf{u}_n \cup \{\min(A^{q_{n+1}} \setminus \mathbf{u}_n)\}$, so $|\mathbf{u}_{n+1}| = n + 1$,
- (e) $E_0^1 = E^p, E_{n+1}^1 = E^{p_n} \upharpoonright (\text{dom}(E^{p_n}) \setminus \bigcup_{i \in \mathbf{u}_n} i/E^{p_n})$,
- (f) q_n is defined as follows:
 - (f₀) if $n = 0$ then $E^{q_n} = E_0^2$,
 - (f₁) if $n > 0$ then $\text{dom}(E^{q_n}) = \text{dom}(E^{p_{n-1}})$ and $x E^{q_n} y$ if and only if either $x E_n^2 y$, or for some $k \in \mathbf{u}_{n-1}$ we have $x, y \in k/E^{p_{n-1}}$, or $x, y \in (\text{dom}(E_n^1) \setminus \text{dom}(E_n^2)) \cup \min(\text{dom}(E_n^2))/E_n^2$,
 - (f₂) H^{q_n} is such that $p_{n-1} \leq q_n$,
- (g) $p_n \leq_n^* q_{n+1} \leq_{n+1}^* p_{n+1}, p_n \leq_{n+1} q_{n+1}$ (so $p_n \leq_{n+1} p_{n+1}$),
- (h) if $f \in \text{var}(\mathbf{u}_n)\{-1, 1\}$ then $p_n^{[f]}$ forces a value to τ_n .

In the first move, when $n = 0$, the first player plays $E_0^1 = E^p$ (as the rules of the game require, according to (e)). The second player answers choosing an I -equivalence relation $E_0^2 \geq E_0^1$. Now, on a side, Player I starts to play the game of 14 using his strategy \mathbf{St}_p . The strategy says him to play a name τ_0 of an ordinal. He defines q_0 by (f) (so $q \in \mathbb{Q}_{I,h}^\ell$ is a condition stronger than p and such that $E^{q_0} = E_0^2$) and chooses a condition $p_0 \geq q_0$ deciding the value of the name τ_0 , say $p_0 \Vdash \tau_0 = \alpha$. He pretends that the second player answered (in the game of 14) by: $p_0, \mathbf{u}_0 = \emptyset, w_0 = \{\alpha\}$. Next, in the play of $GM_I(E^p)$, he plays $E_1^1 = E^{p_0}$ as declared in (e).

Now suppose that we are at the $(n + 1)^{\text{th}}$ stage of the play of $GM_I(E^p)$, the first player has played E_{n+1}^1 already and on a side he has played the play of the game 14 as defined by (a)–(h) and \mathbf{St}_p (so in particular he has defined a condition p_n and $E_{n+1}^1 = E^{p_n} \upharpoonright (\text{dom}(E^{p_n}) \setminus \bigcup_{i \in \mathbf{u}_n} i/E^{p_n})$ and \mathbf{u}_n is the set of

the first n elements of A^{p_n}). The second player plays an I -equivalence relation $E_{n+1}^2 \geq E_{n+1}^1$. Now the first player chooses (on a side, pretending to play in the game of 14): a name τ_{n+1} given by the strategy \mathbf{St}_p , a condition $q_{n+1} \in \mathbb{Q}_{I,h}^\ell$ determined by (f) (check that (g) is satisfied), \mathbf{u}_{n+1} as in (d) and a condition $p_{n+1} \in \mathbb{Q}_{I,h}^\ell$ satisfying (g), (h) (the last exists by 10). Note that, by (g) and 9, the condition p_{n+1} determines a suitable set w_{n+1} . Thus, Player I pretends that his opponent in the game of 14 played $p_{n+1}, \mathbf{u}_{n+1}, w_{n+1}$ and he passes to the actual game $GM_I(E^p)$. Here he plays E_{n+2}^1 defined by (e).

The strategy \mathbf{St} described above cannot be the winning one. Consequently, there is a play in $GM_I(E^p)$ in which Player I uses \mathbf{St} , but he loses. During the play he constructed a sequence $\langle (p_n, \mathbf{u}_n, w_n) : n \in \omega \rangle$ of legal moves of Player II in the game of 14 against the strategy \mathbf{St}_p . Let $E^q = \lim_{n < \omega} E^{p_n}$ (i.e. $\text{dom}(E^q) = \bigcap_{n < \omega} \text{dom}(E^{p_n})$, $x E^q y$ if and only if for every large enough n , $x E^{p_n} y$) and let $H^q(x_i^m)$ will be $H^{p_n}(x_i^m)$ for any large enough n (it is eventually constant). It follows from the demand (g) that E^q -equivalence classes are in I . Moreover, $\text{dom}(E_{n+1}^1) \setminus \text{dom}(E_{n+1}^2) \subseteq k/E^q$, where k is the $(n + 1)^{\text{th}}$ member of A^q . Therefore

$$\omega \setminus \text{dom}(E^q) = \omega \setminus \bigcap_{n \in \omega} \text{dom}(E^{p_n}) \subseteq \omega \setminus \text{dom}(E^{p_0}) \cup \bigcup \{ \text{dom}(E_n^2) \setminus \text{dom}(E_{n+1}^1) : n \in \omega \} \in I$$

(remember, Player I lost in $GM_I(E^p)$). Now it should be clear that $q \in \mathbb{Q}_{I,h}^\ell$ and it is stronger than every p_n (even $p_n \leq_n^* q$). Hence Player II wins the corresponding play of 14, showing that \mathbf{St}_p is not a winning strategy.

- 2) The same proof. ■

Proposition 15. If in 14 we assume $\ell = 2$ and demand $p_n \leq_n^\otimes p_{n+1}$ instead $p_n \leq_n^* p_{n+1}$ then Player II has a winning strategy.

PROOF Using 11, the second player can find suitable conditions p_n (in the game of 14) such that $p_n \leq_{n+1}^\otimes p_{n+1}$. But note that the partial orders \leq_n^\otimes have the fusion property, so the sequence $\langle p_n : n < \omega \rangle$ will have an upper bound in $\mathbb{Q}_{I,h}^2$. ■

Remark. We could have used $<_n^\otimes$ also in [Sh 407].

Definition 16 see [Sh:f, VI, 2.12, A-F].

1. A forcing notion \mathbb{P} has the PP-property if:
 - (\otimes^{PP}) for every $\eta \in {}^\omega\omega$ from $\mathbf{V}^{\mathbb{P}}$ and a strictly increasing $x \in {}^\omega\omega \cap \mathbf{V}$ there is a closed subtree $T \subseteq {}^{<\omega}\omega$ such that:
 - (α) $\eta \in \text{lim}(T)$, i.e. $(\forall n < \omega)(\eta \upharpoonright n \in T)$,
 - (β) $T \cap {}^n\omega$ is finite for each $n < \omega$,
 - (γ) for arbitrarily large n there are k , and $n < i(0) < j(0) < i(1) < j(1) < \dots < i(k) < j(k) < \omega$ and for each $\ell \leq k$, there are $m(\ell) < \omega$ and $\eta^{\ell,0}, \dots, \eta^{\ell,m(\ell)} \in T \cap {}^{j(\ell)}\omega$ such that $j(\ell) > x(i(\ell) + m(\ell))$ and

$$(\forall \nu \in T \cap {}^{j(k)}\omega)(\exists \ell \leq k)(\exists m \leq m(\ell))(\eta^{\ell,m} \trianglelefteq \nu).$$

2. We say that a forcing notion \mathbb{P} has the strong PP-property if
 - (\oplus^{sPP}) for every function $g : \omega \rightarrow \mathbf{V}$ from $\mathbf{V}^{\mathbb{P}}$ there exist a set $B \in [\omega]^{\aleph_0} \cap \mathbf{V}$ and a sequence $\langle w_n : n \in B \rangle \in \mathbf{V}$ such that for each $n \in B$

$$|w_n| \leq n \quad \text{and} \quad g(n) \in w_n.$$

Remark. Of course, if a proper forcing notion has the strong PP-property then it has the PP-property.

Conclusion 17 Assume that for each $p \in \mathbb{Q}_{I,h}^\ell$ and for each countable $N \prec (\mathcal{H}(\chi), \in, <^*)$ such that $p, I, h \in N$, the first player has no winning strategy in $GM_I^N(E^p)$ (e.g. if I is a maximal ideal). Then

- (*) $\mathbb{Q}_{I,h}^\ell$ is proper, α -proper, strongly α -proper for every $\alpha < \omega_1$, is ${}^\omega\omega$ -bounding and it has the PP-property, even the strong PP-property. ■

By [Sh:f, VI, 2.12] we know

Theorem 18. Suppose that $\langle \mathbb{P}_i, \mathbb{Q}_j : j < \alpha, i \leq \alpha \rangle$ is a countable support iteration such that

$$\Vdash_{\mathbb{P}_j} \text{“}\mathbb{Q}_j \text{ is proper and has the PP-property”}.$$

Then \mathbb{P}_α has the PP-property. ■

2 NWD ultrafilters

A subset A of the set \mathcal{Q} of rationals is *nowhere dense* (NWD) if its closure (in \mathcal{Q}) has empty interior. Remember that the rationals are equipped with the order topology and both “closure” and “interior” refer to this topology. Of course, as \mathcal{Q} is dense in the real line, we may consider these operations on the real line and get the same notion of nowhere dense sets. For technical reasons, in forcing considerations we prefer to work with ${}^\omega 2$ instead of the real line. So naturally we want to replace rationals by ${}^{<\omega}2$. But what are nowhere dense subsets of

${}^{<\omega}2$ then? (One may worry about the way we “embed” ${}^{<\omega}2$ into ${}^\omega 2$.) Note that we have a natural lexicographical ordering $<_{tx}$ of ${}^{<\omega}2$:

- $\eta <_{tx} \nu$ if and only if
 - either there is $\ell < \omega$ such that $\eta \upharpoonright \ell = \nu \upharpoonright \ell$ and $\eta(\ell) < \nu(\ell)$
 - or $\eta \upharpoonright \langle 1 \rangle \trianglelefteq \nu$
 - or $\nu \upharpoonright \langle 0 \rangle \trianglelefteq \eta$.

Clearly $({}^{<\omega}2, <_{tx})$ is a linear dense order without end-points (and consequently it is order-isomorphic to the rationals). Now, we may talk about nowhere dense subsets of ${}^{<\omega}2$ looking at this ordering only, but we may relate this notion to the topology of ${}^\omega 2$ as well.

Proposition 19. For a set $A \subseteq {}^{<\omega}2$ the following conditions are equivalent:

1. A is nowhere dense,
2. $(\forall \eta \in {}^{<\omega}2)(\exists \nu \in {}^{<\omega}2)[\eta \trianglelefteq \nu \ \& \ (\forall \rho \in {}^{<\omega}2)(\nu \trianglelefteq \rho \Rightarrow \rho \notin A)]$,
3. the set

$$A^* \stackrel{\text{def}}{=} \{ \eta \in {}^\omega 2 : (\forall n \in \omega)(\exists \nu \in A)(\eta \upharpoonright n \trianglelefteq \nu) \}$$

is nowhere dense (in the product topology of ${}^\omega 2$),

4. there is a sequence $\langle \eta_n : n < \omega \rangle$ such that for each $n < \omega$
 - (i) $_n$ $\eta_n : [n, \ell_n) \rightarrow 2$ for some $\ell_n > n$ and
 - (ii) $_n$ $(\forall \rho \in A)(\eta_n \not\subseteq \rho)$,
5. there is a sequence $\langle \eta_n : n < \omega \rangle$ such that for each $n < \omega$ condition (i) $_n$ (see above) holds and
 - (ii) $_n^*$ $(\forall \nu \in {}^n 2)(\{ \rho \in {}^{<\omega}2 : \nu \cup \eta_n \trianglelefteq \rho \} \cap A = \emptyset)$,
6. there are $B \in [\omega]^{\aleph_0}$ and $\langle \eta_n : n \in B \rangle$ such that for each $n \in B$ the conditions (i) $_n$, (ii) $_n$ above are satisfied.

PROOF 1. \Rightarrow 2. Suppose $A \subseteq {}^{<\omega}2$ is nowhere dense but for some sequence $\eta \in {}^{<\omega}2$, for every $\nu \in {}^{<\omega}2$ extending η there is $\rho \in A$ such that $\nu \trianglelefteq \rho$. Look at the interval $(\eta \upharpoonright \langle 0 \rangle, \eta \upharpoonright \langle 1 \rangle)_{<tx}$ (of $({}^{<\omega}2, <_{tx})$). We claim that A is dense in this interval. Why? Suppose

$$\eta \upharpoonright \langle 0 \rangle \leq_{tx} \eta_0^* <_{tx} \eta_1^* \leq_{tx} \eta \upharpoonright \langle 1 \rangle.$$

Assume $\ell g(\eta_0^*) \leq \ell g(\eta_1^*)$. Take $\nu \stackrel{\text{def}}{=} \eta_1^* \upharpoonright \langle 0 \rangle$. By the definition of the order $<_{tx}$ we have then

$$\eta_0^* <_{tx} \nu \upharpoonright \langle 0 \rangle <_{tx} \nu \upharpoonright \langle 1 \rangle <_{tx} \eta_1^* \quad \text{and} \quad \eta \trianglelefteq \nu.$$

By our assumption we find $\rho \in A$ such that $\nu \upharpoonright \langle 0, 1 \rangle \trianglelefteq \rho$. Then

$$\nu \upharpoonright \langle 0 \rangle <_{tx} \rho <_{tx} \nu \upharpoonright \langle 1 \rangle \quad \text{and hence} \quad \rho \in (\eta_0^*, \eta_1^*)_{<tx}.$$

Similarly if $\ell g(\eta_1^*) \leq \ell g(\eta_0^*)$.

2. \Rightarrow 3. Should be clear if you remember that sets

$$[\nu] \stackrel{\text{def}}{=} \{ \eta \in {}^\omega 2 : \nu \triangleleft \eta \} \quad (\text{for } \nu \in {}^{<\omega}2)$$

constitute the basis of the topology of ${}^\omega 2$.

3. \Rightarrow 4. Suppose A^* is nowhere dense in ${}^\omega 2$. Let $n < \omega$. Considering all elements of 2^n build (e.g. inductively) a function $\eta_n^* : [n, \ell_n^*) \rightarrow 2$ such that $n < \ell_n^*$ and

$$(\forall \nu \in 2^n)([\nu \widehat{\eta}_n^*] \cap A^* = \emptyset).$$

This means that for each $\nu \in 2^n$ the set $\{\rho \in A : \nu \widehat{\eta}_n^* \leq \rho\}$ is finite (otherwise use König lemma to construct an element of A^* in $[\nu \widehat{\eta}_n^*]$). Taking sufficiently large $\ell_n > \ell_n^*$ and extending η_n^* to η_n with domain $[n, \ell_n)$ we get that $(\forall \rho \in A)(\eta_n \not\leq \rho)$ (as required).

4. \Rightarrow 5. \Rightarrow 6. Read the conditions.

6. \Rightarrow 1. Let $B, \langle \eta_n : n \in B \rangle$ be as in 6. Suppose $\nu_0, \nu_1 \in {}^{<\omega} 2$, $\nu_0 <_{tx} \nu_1$. Assume $lg(\nu_0) \leq lg(\nu_1) = m$. Take any $n \in B \setminus (m+1)$ and let $\nu = \nu_1 \widehat{\langle 0, \dots, 0 \rangle}_{n-m} \widehat{\eta}_n$. We know that no element of A extends ν . But this implies

that the interval $(\nu \widehat{\langle 0 \rangle}, \nu \widehat{\langle 1 \rangle})_{<tx}$ is disjoint from A (and is contained in the interval $(\nu_0, \nu_1)_{<tx}$). Similarly if $lg(\nu_1) \leq lg(\nu_0)$. \blacksquare

Lemma 20. Let $n, k^* < \omega$. Assume that $\bar{\nu}^k = \langle \nu_i^k : n \leq i < i_k \rangle$ for $k < k^* < \omega$, $n \leq i_k < \omega$, $\nu_i^k \in \bigcup_{j \geq i}^{[i, j)} 2$ and $w_k \subseteq [n, i_k)$, $|w_k| \geq k^*$ and:

if $k < k^*$, $m_1 < m_2$ are in w_k then $\max \text{dom}(\nu_{m_1}^k) < m_2$.

Lastly let

$$i(*) = \max\{\sup \text{dom}(\nu_i^k) + 1 : k < k^* \text{ and } i \in (n, i_k)\}.$$

Then we can find $\rho \in [n, i(*)_2$ such that:

$$(\forall k < k^*)(\exists i \in w_k)(\nu_i^k \subseteq \rho).$$

PROOF By induction on k^* (for all possible other parameters). For $k^* = 0, 1$ it is trivial.

Let $n_k^0 = \min(w_k)$ and $n_k^1 = \min(w_k \setminus (n_k^0 + 1))$. Let $\ell < k^*$ be with minimal n_ℓ^1 . Apply the induction hypothesis with $n_\ell^1, \bar{\nu}^\ell = \langle \nu_i^\ell : n_\ell^1 \leq i < i_k \rangle$ for $k < k^*$, $k \neq \ell$ and $\langle w_k \setminus n_\ell^1 : k < k^*, k \neq \ell \rangle$ here standing for $n, \bar{\nu}^k$ for $k < k^*$, $\langle w_k : k < k^* \rangle$ there and get $\rho_1 \in [n_\ell^1, i(*)_2$. Note that $w_k \setminus n_\ell^1 \supseteq w_k \setminus n_k^1$ has at least $|w_k| - 1$ elements. Let $\rho \in [n, i(*)_2$ be such that $\rho_1 \subseteq \rho$ and $\bar{\nu}_{n_\ell^1}^\ell \subseteq \rho$. \blacksquare

Proposition 21. Assume that \mathbb{R} is a proper forcing notion with the PP-property. Then

(\oplus^{nwd}) for every nowhere dense set $A \subseteq {}^{<\omega} 2$ in $\mathbf{V}^{\mathbb{R}}$ there is a nowhere dense set $A^* \subseteq {}^{<\omega} 2$ in \mathbf{V} such that $A \subseteq A^*$.

PROOF Let $A \in \mathbf{V}^{\mathbb{R}}$ be a nowhere dense subset of ${}^{<\omega} 2$. Thus, in $\mathbf{V}^{\mathbb{R}}$, we can, for each $n < \omega$, choose $\nu_n \in \bigcup_{\ell \geq n}^{[n, \ell)} 2$ such that:

$$(\forall \nu \in {}^{n_2})(\forall \rho \in {}^{<\omega} 2)(\nu \widehat{\nu}_n \leq \rho \Rightarrow \rho \notin A).$$

So $\langle \nu_n : n < \omega \rangle \in \mathbf{V}^{\mathbb{R}}$ is well defined. Next for each n we choose an integer $\ell_n \in (n, \omega)$, a sequence $\eta_n \in [n, \ell_n)_2$ and a set $w_n \subseteq [n, \ell_n)$ such that:

- $|w_n| > n$,
- $(\forall m \in w_n)(\nu_m \subseteq \eta_n)$, so in particular $(\forall m \in w_n)(\max \text{dom}(\nu_m) < \ell_n)$, and
- for any $m_1 < m_2$ from w_n we have $\max \text{dom}(\nu_{m_1}) < m_2$.

So $\bar{w} = \langle w_n : n < \omega \rangle, \bar{\eta} = \langle \eta_n : n < \omega \rangle \in \mathbf{V}^{\mathbb{R}}$ are well defined.

Since \mathbb{R} has the PP-property it is ${}^\omega \omega$ -bounding, and hence there is a strictly increasing $x \in {}^\omega \omega \cap \mathbf{V}$ such that $(\forall n \in \omega)(\ell_n < x(n))$. Applying the PP-property of \mathbb{R} to x and the function $n \mapsto \langle \eta_n, w_n \rangle$ we can find $\langle \langle V_\ell^n : \ell \leq k_n \rangle : n < \omega \rangle$ in \mathbf{V} and $\langle \langle (i_\ell(n), j_\ell(n)) : \ell \leq k_n \rangle : n < \omega \rangle$ in \mathbf{V} such that:

- (a) $i_0(n) < j_0(n) < i_1(n) < j_1(n) < \dots < i_{k_n}(n) < j_{k_n}(n)$,
- (b) $j_{k_n}(n) < i_0(n+1)$ for $n < \omega$,
- (c) $x(i_\ell(n)) < x(j_\ell(n))$,
- (d) $V_\ell^n \subseteq \{(\eta, w) : \eta \in [i_\ell(n), j_\ell(n))_2 \text{ and } w \subseteq [i_\ell(n), j_\ell(n)), |w| > i_\ell(n)\}$ for $\ell \leq k_n, n < \omega$,
- (e) $|V_\ell^n| \leq i_\ell(n)$,
- (f) for every $n < \omega$, for some $\ell \leq k_n$ and $(\eta, w) \in V_\ell^n$ we have $w = w_{i_\ell(n)}$, $\eta_{i_\ell(n)} \subseteq \eta$.

[Note that $i_\ell(n)$ corresponds to $i(\ell) + m(\ell)$ in definition 16(1), so we do not have $m_\ell(n)$ here.] Working in \mathbf{V} , by 20, for each $n < \omega$, $\ell \leq k_n$ there is $\rho_\ell^n \in [i_\ell(n), j_\ell(n))_2$ such that:

$$(\forall (\eta, w) \in V_\ell^n)(\exists m_1, m_2 \in w)(m_2 = \min(w \setminus (m_1 + 1)) \ \& \ \eta \upharpoonright [m_1, m_2] \subseteq \rho_\ell^n).$$

Let $\rho_n \in [i_0(n), i_0(n+1))_2$ be such that $\ell \leq k_n \Rightarrow \rho_\ell^n \subseteq \rho_n$. As we have worked in \mathbf{V} , $\langle \rho_n : n < \omega \rangle \in \mathbf{V}$. Let

$$A^* = \{\rho \in {}^{<\omega} 2 : \neg(\exists n \in \omega)(\rho_n \subseteq \rho)\}.$$

Clearly $A^* \in \mathbf{V}$ is as required. \blacksquare

Let us recall definition 1 reformulating it slightly for technical purposes. (Of course, the two definitions are equivalent; see the discussion at the beginning of this section.)

Definition 22. We say that a non-principal ultrafilter \mathcal{D} on ω is an NWD-ultrafilter if for any sequence $\langle \eta_n : n < \omega \rangle \subseteq {}^{<\omega} 2$ for some $A \in \mathcal{D}$ the set $\{\eta_n : n \in A\}$ is nowhere dense in ${}^{<\omega} 2$.

Lemma 23. Let \mathcal{D} be a non-principal ultrafilter on ω and I be the dual ideal (and $h : \omega \rightarrow \omega$ non-decreasing $\lim_{n \rightarrow \infty} h(n) = \infty$). Then:

1. in $\mathbf{V}^{\mathbb{Q}_{I,h}^1}$ we cannot extend \mathcal{D} to an NWD-ultrafilter.
2. If \mathbb{Q} is a $\mathbb{Q}_{I,h}^1$ -name of a proper forcing notion with the PP-property, then also in $\mathbf{V}^{\mathbb{Q}_{I,h}^1 * \mathbb{Q}}$ we cannot extend \mathcal{D} to an NWD-ultrafilter.

PROOF 1) Let $\bar{\eta} = \langle \eta_n : n < \omega \rangle$ be the name defined in 6, but now we interpret the value -1 as 0 . So $\Vdash \eta_n \in {}^{h(n)}2$ (for each $n < \omega$). Clearly it is enough to show that

$$(*) \quad \Vdash_{\mathbb{Q}_{I,h}^1} \text{ "if } X \subseteq \omega \text{ and the set } \{\eta_n : n \in X\} \text{ is nowhere dense then there is } Y \in \mathcal{D} \text{ disjoint from } X \text{."}$$

So suppose that τ is a $\mathbb{Q}_{I,h}^1$ -name for a subset of ω and a condition $p^* \in \mathbb{Q}_{I,h}^1$ forces that $\{\eta_n : n \in \tau\}$ is nowhere dense.

By 19, for some $\mathbb{Q}_{I,h}^1$ -names $\bar{\nu} = \langle \nu_m : m < \omega \rangle$ we have

$$p^* \Vdash \nu_m \in \bigcup_{\ell \geq m} {}^{[m,\ell]}2 \text{ and for every } m < \omega \text{ for no } n \in \tau \text{ we have } \nu_m \subseteq \eta_n \text{."}$$

By 14 (or actually by its proof) without loss of generality:

for every $n \in A^{p^*}$, for some $k_n \in (n, \min(A^{p^*} \setminus (n+1)))$, for every $f : \{x_j^m : m \in A^{p^*} \cap (n+1) \text{ and } j < h(m)\} \rightarrow \{-1, 1\}$, the condition $p^{*[f]}$ forces a value to $\tau \cap k_n$, and $\tau \cap k_n \setminus n \neq \emptyset$.

[Why? Give a strategy to Player I in the game there for p^* trying to force the needed information, so for some such play Player II wins and replaces p^* by q from there.]

Again by 14 we may assume that

for every $f : \{x_j^m : j < h(m) \text{ and } m \in A^{p^*} \cap (n+1)\} \rightarrow \{-1, 1\}$, $n \in A^{p^*}$, for some $\bar{\nu}^f$ we have

$$p^{*[f]} \Vdash \bar{\nu}^f \text{ is an initial segment of } \bar{\nu} \text{ and } \ell g(\bar{\nu}^f) = n+1 \text{."}$$

For $n \in A^{p^*}$ and $f : \{x_j^m : j < h(m) \text{ and } m \in A^{p^*} \cap (n+1)\} \rightarrow \{-1, 1\}$ and $k \in A^{p^*} \setminus (n+1)$ let:

- (a) $f^{[k,p^*]}$ be the function with domain $\{x_j^m : j < h(m) \text{ and } m \in A^{p^*} \cap (k+1)\}$ extending f that is constantly 1 on $\text{dom}(f^{[k,p^*]}) \setminus \text{dom}(f)$,
- (b) $\bar{\rho}^f$ be an ω -sequence $\langle \rho_\ell^f : \ell < \omega \rangle$ such that for each $k \in A^{p^*} \setminus (n+1)$ we have $\bar{\rho}^f \upharpoonright (k+1) = \bar{\nu}^{f^{[k,p^*]}} \upharpoonright (k+1)$.

Now, for every $n \in A^{p^*}$, we can find $\rho_n^* \in {}^{<\omega}2$ such that for every function

$$f : \{x_j^m : j < h(m) \text{ and } m \in A^{p^*} \cap (n+1)\} \rightarrow \{-1, 1\}$$

for some $\ell(f) \in (h(n), \omega)$ we have $\rho_{\ell(f)}^f \subseteq \rho_n^*$ (so $\ell(f) < \ell g(\rho_n^*)$).

[Why? Let $\{f_j : j < j^*\}$ list the possible f 's, and we chose by induction on $j \leq j^*$, $\rho^j \in {}^{<\omega}2$ such that $\rho^j \triangleleft \rho^{j+1}$, and ρ^{j+1} satisfies the requirement on f_j , e.g. $\rho_0 = \langle 0, \dots, 0 \rangle$, $\rho^{j+1} = \rho^j \hat{\sim} \rho_{\ell g(\rho^j)}^{f_j}$.]

Now choose by induction on $\zeta < \omega$, $n_\zeta \in A^{p^*}$ such that $n_\zeta < n_{\zeta+1}$, and $\ell g(\rho_{n_\zeta}^*) < h(n_{\zeta+1})$. Without loss of generality $\bigcup_{\zeta < \omega} (n_\zeta / E^{p^*}) \in I$. Then

$$\text{either } \bigcup \{n / E^{p^*} : n \in A^{p^*} \text{ and } (\exists \zeta < \omega)(n_{2\zeta} < n < n_{2\zeta+1})\} \in \mathcal{D} \\ \text{or } \bigcup \{n / E^{p^*} : n \in A^{p^*} \text{ and } (\exists \zeta < \omega)(n_{2\zeta+1} < n < n_{2\zeta+2})\} \in \mathcal{D},$$

so by renaming the latter holds. (Again, it suffices that the ideal I is such that the quotient algebra $\mathcal{P}(\omega)/I$ satisfies the c.c.c.) Lastly we define a condition $r \in \mathbb{Q}_{I,h}^1$:

$$\text{dom}(E^r) = \bigcup_{\zeta < \omega} n_{2\zeta} / E^{p^*} \cup \bigcup \{n / E^{p^*} : n \in A^{p^*} \text{ and } (\exists \zeta < \omega)(n_{2\zeta+1} < n < n_{2\zeta+2})\},$$

$$n_{2\zeta} / E^r = (n_{2\zeta} / E^{p^*}) \cup \bigcup \{m / E^{p^*} : m \in A^{p^*} \cap (n_{2\zeta+1}, n_{2\zeta+2})\}$$

(note that this defines correctly an I -equivalence relation E^r), $A^r = \{n_{2\zeta} : \zeta < \omega\}$. The function H^r is defined by cases (interpreting the value 0 as -1 , where appears):

$$H^r(x_j^m) = H^{p^*}(x_j^m) \text{ if } m \in (\omega \setminus \text{dom}(E^{p^*})) \text{ and } j < h(m), \\ H^r(x_j^m) = H^{p^*}(x_j^m) \text{ if } m \in \text{dom}(E^{p^*}) \text{ and } j \in [h(\min(m/E^{p^*})), h(m)) \\ H^r(x_j^m) = 1 \text{ if } m \in \text{dom}(E^{p^*}) \text{ and } \min(m/E^{p^*}) \in (n_{2\zeta}, n_{2\zeta+1}) \\ \text{and } j < h(\min(m/E^{p^*})) \\ H^r(x_j^m) = \rho_{n_{2\zeta}}^*(j) \text{ if } m \in \text{dom}(E^{p^*}) \text{ and } \min(m/E^{p^*}) \in (n_{2\zeta+1}, n_{2\zeta+2}) \\ \text{and } j \in \text{dom}(\rho_{n_{2\zeta}}^*) \text{ and } j \geq h(n_{2\zeta}) \\ H^r(x_j^m) = 1 \text{ otherwise (but } x_j^m \in \text{dom}(H^r)).$$

Now check that $p^* \leq r \in \mathbb{Q}_{I,h}^1$ and for each $n \in \text{dom}(E^r) \setminus \bigcup_{\zeta < \omega} n_{2\zeta} / E^{p^*}$:

$$r \Vdash \eta_n \text{ violates the property of } \bar{\nu} \text{ and hence } n \notin \tau \text{."}$$

As $\text{dom}(E^r) \setminus \bigcup_{\zeta < \omega} n_{2\zeta} / E^{p^*} \in \mathcal{D}$ we have finished.

2) Should be clear by (*) of the proof of 23(1) and 21.

However we will give an alternative proof of 23(2). We start as in the proof of 23(1): suppose some $(p^*, r^*) \in \mathbb{Q}_{I,h}^1 * \mathbb{Q}$ forces " F is an NWD-ultrafilter on ω

extending D ". As $\Vdash \eta_n[G_{\mathbb{Q}_{I,h}^1}] \in {}^{h(n)}2$, for some $(\mathbb{Q}_{I,h}^1 * \mathbb{Q})$ -name τ for a subset of ω

$$(p^*, r^*) \Vdash \tau \in F \text{ and } (\forall \eta \in {}^{<\omega}2)(\exists \nu \in {}^{<\omega}2)(\eta \sqsubseteq \nu \ \& \ (\forall n \in \tau)(\neg \nu \sqsubseteq \eta_n))$$

So for some $\mathbb{Q}_{I,h}^1 * \mathbb{Q}$ -name $\bar{\nu} = \langle \nu_n : n < \omega \rangle$

$$(p^*, r^*) \Vdash \nu_\ell \in \bigcup_{j \in [\ell, \omega]} {}^{[\ell, j]}2 \text{ and for no } n \in \tau \text{ we have } \nu_\ell \subseteq \eta_n$$

So for some $\mathbb{Q}_{I,h}^1 * \mathbb{Q}$ -names d_ℓ, ψ_ℓ

$$(p^*, r^*) \Vdash \omega > d_\ell > \ell, \ \psi_\ell \subseteq [\ell, d_\ell], \ |\psi_\ell| > (4 \cdot \prod_{s \leq n} h(s))! \text{ and } [m_1 < m_2 \text{ in } \psi_\ell \Rightarrow \max \text{dom}(\nu_{m_1}) < m_2]$$

Let $p^* \in G_{\mathbb{Q}_{I,h}^1} \subseteq \mathbb{Q}_{I,h}^1$ and $G_{\mathbb{Q}_{I,h}^1}$ generic over \mathbf{V} . Now in $\mathbf{V}[G_{\mathbb{Q}_{I,h}^1}]$, the forcing notion $\mathbb{Q}[G_{\mathbb{Q}_{I,h}^1}]$ is ${}^\omega\omega$ -bounding (this follows from the PP-property) and also $\mathbb{Q}_{I,h}^1$ is ${}^\omega\omega$ -bounding.

Hence for some $r' \in \mathbb{Q}[G_{\mathbb{Q}_{I,h}^1}]$ and strictly increasing $x \in {}^\omega\omega \cap \mathbf{V}$ we have:

$$r' \Vdash_{\mathbb{Q}[G_{\mathbb{Q}_{I,h}^1}]} \text{“} d_n < x(n) \text{ and } m \in \psi_n \Rightarrow \text{dom}(\nu_m) \subseteq [0, x(n)]\text{”}$$

In $\mathbf{V}[G_{\mathbb{Q}_{I,h}^1}]$, by the property of \mathbb{Q} , there are $r^{**}, r' \leq r^{**} \in \mathbb{Q}[G_{\mathbb{Q}_{I,h}^1}]$ and a sequence $\langle \langle i_\ell(n), j_\ell(n) \rangle : \ell \leq k_n \rangle : n < \omega \rangle$ such that

$$i_0(n) < j_0(n) < i_1(n) < j_1(n) < \dots < j_{k_n}(n) < i_\ell(n+1), j_\ell(n) > x(i_\ell(n))$$

and there are $\bar{\nu}_{n,\ell,t}^* = \langle \nu_{n,\ell,t,j}^* : j \in [i_\ell(n), j_\ell(n)] \rangle$ for $t < i_\ell(n), \ell \leq k_n$ and $\bar{w}_{n,\ell,t}^* = \langle w_{n,\ell,t,j}^* : j \in [i_\ell(n), i_{\ell+1}(n)] \rangle$ for $t < i_\ell(n), \ell \leq k_n$ such that

$$r^{**} \Vdash_{\mathbb{Q}} \text{“} \langle \nu_{i_\ell(n)+j}^* : j \in [i_\ell(n), j_\ell(n)] \rangle \text{ is } \bar{\nu}_{n,\ell,t}^* \text{ and } \langle w_{i_\ell(n)+j}^* : j \in [i_\ell(n), j_\ell(n)] \rangle \text{ is } \bar{w}_{n,\ell,t}^* \text{ for some } t < i_\ell(n)\text{”}$$

Back in \mathbf{V} we have a $\mathbb{Q}_{I,h}^1$ -name r^{**} and $\langle \langle (i_\ell(n), j_\ell(n)) : \ell \leq k_n \rangle : n < \omega \rangle$ and $\langle \langle \bar{\nu}_{n,\ell,t}^* : t < i_\ell(n) \rangle : \ell < k_n, n < \omega \rangle$ and $\langle \langle \bar{w}_{n,\ell,t}^* : t < i_\ell(n) \rangle : \ell < k_n, n < \omega \rangle$ are forcing (by p^*) to be as above.

By 14, increasing p^* , we get

for every $f : \{x_i^n : i < h(m), m \in A^{p^*} \cap (n+1)\} \rightarrow \{-1, 1\}, n \in A^{p^*}$, the condition $p^{*(f)}$ forces a value to

$$\begin{aligned} & \langle \langle (i_\ell(m), j_\ell(m)) : \ell \leq k_m \rangle : m \leq n \rangle, \\ & \langle \bar{\nu}_{n,\ell,t}^* : t < i_\ell(n), \ell \leq k_n \rangle, \\ & \langle \bar{w}_{n,\ell,t}^* : t < i_\ell(n), \ell < k_n \rangle \end{aligned}$$

moreover, without loss of generality

$$n \in A^{p^*} \Rightarrow j_{k_n}(n) < \min(A^{p^*} \setminus (n+1)).$$

Now by 20, without loss of generality for each $n \in A^{p^*}$ we can find a function ρ_n from $[n, \min(A^{p^*} \setminus (n+1))]$ to $\{-1, 1\}$ such that:

$$\begin{aligned} & \text{if } f : \{x_i^m : i < h(m), m \in A^{p^*} \cap (n+1)\} \rightarrow \{-1, 1\}, n \in A^{p^*} \\ & \text{then } (p^{*(f)}, r^{**}) \text{ forces that } \rho_n \text{ extends some } \nu_\ell. \end{aligned}$$

Now we continue as in the proof of 23(1). \blacksquare

3 The consistency proof

Theorem 24. Assume CH and $\diamond_{\{\gamma < \omega_2 : \text{cf}(\gamma) = \omega_1\}}$.

Then there is an \aleph_2 -cc proper forcing notion \mathbb{P} of cardinality \aleph_2 such that

$$\Vdash_{\mathbb{P}} \text{“there are no NWD-ultrafilters on } \omega \text{”}$$

PROOF Define a countable support iteration $\langle \mathbb{P}_i, \mathbb{Q}_j : i \leq \omega_2, j < \omega_2 \rangle$ of proper forcing notions and sequences $\langle \mathcal{D}_i : i < \omega_2 \rangle$ and $\langle \bar{\eta}^i : i < \omega_2 \rangle$ such that for each $i < \omega_2$:

1. \mathcal{D}_i is a \mathbb{P}_i -name for a non-principal ultrafilter on ω ,
2. \mathbb{Q}_i is a \mathbb{P}_i -name for a proper forcing notion of size \aleph_1 with the PP-property,
3. $\bar{\eta}^i$ is a $\mathbb{P}_i * \mathbb{Q}_i$ -name for a function from ω to ${}^{<\omega}2$,
4. $\Vdash_{\mathbb{P}_i * \mathbb{Q}_i}$ “if $X \subseteq \omega$ and the set $\{\eta_n^i : n \in X\} \subseteq {}^{<\omega}2$ is nowhere dense then there is $Y \in \mathcal{D}_i$ disjoint from X ”,
5. if \mathcal{D} is a \mathbb{P}_{ω_2} -name for an ultrafilter on ω then the set

$$\{i < \omega_2 : \text{cf}(i) = \omega_1 \ \& \ \mathcal{D}_i = \mathcal{D} \upharpoonright \mathcal{P}(\omega)^{\mathbf{V}^{\mathbb{P}_i}}\}$$

is stationary.

Let us first argue that if we succeed with the construction then, in $\mathbf{V}^{\mathbb{P}_{\omega_2}}$, we will have

$$2^{\aleph_0} = \aleph_2 + \text{“there is no NWD-ultrafilter on } \omega \text{”}$$

Why? As each \mathbb{Q}_i is (a name for) a proper forcing notion of size \aleph_1 , the limit \mathbb{P}_{ω_2} is a proper forcing notion with a dense subset of size \aleph_2 and satisfying the \aleph_2 -cc. Since \mathbb{P}_{ω_2} is proper, each subset of ω (in $\mathbf{V}^{\mathbb{P}_{\omega_2}}$) has a canonical countable name (i.e. a name which is a sequence of countable antichains; every condition in the n^{th} antichain decides if the integer n is in the set or not; of course we do not require that the antichains are maximal). Hence $\Vdash_{\mathbb{P}_{\omega_2}} 2^{\aleph_0} \leq \aleph_2$ (remember that we have assumed $\mathbf{V} \models \text{CH}$). Moreover, by 18 + 21 we know that \mathbb{P}_{ω_2} satisfies (\oplus^{nwd}) of 21, i.e.

$$\Vdash_{\mathbb{P}_{\omega_2}} \text{“each nowhere dense subset of } {}^{<\omega}2 \text{ can be covered by a nowhere dense subset of } {}^{<\omega}2 \text{ from } \mathbf{V}\text{”}$$

Now suppose that \mathcal{D} is a \mathbb{P}_{ω_2} -name for an ultrafilter on ω . By the fifth requirement, we find $i < \omega_2$ such that $\mathcal{D}_i = \mathcal{D} \upharpoonright \mathcal{P}(\omega)^{\mathbf{V}^{\mathbb{P}_i}}$ (and $\text{cf}(i) = \omega_1$). Since \mathbb{P}_{ω_2} satisfies (\oplus^{nwd}) , we have

$\Vdash_{\mathbb{P}_{\omega_2}}$ "if $X \subseteq \omega$ and the set $\{\eta_n^i : n \in X\} \subseteq {}^{<\omega}2$ is nowhere dense then there is an element of $\mathcal{D}[\mathcal{P}(\omega)]^{\mathbb{V}^{\mathbb{P}_i}}$ disjoint from X "

[Why? Cover $\{\eta_n^i : n \in X\}$ by a nowhere dense set $A \subseteq {}^{<\omega}2$ from \mathbb{V} and look at the set $X_0 = \{n \in \omega : \eta_n^i \in A\}$. Clearly $X_0 \in \mathbb{V}^{\mathbb{P}_i}$ and $X \subseteq X_0$. Applying the fourth clause to X_0 we find $Y \in \mathcal{D}_i = \mathcal{D}[\mathcal{P}(\omega)]^{\mathbb{V}^{\mathbb{P}_i}}$ such that $Y \cap X_0 = \emptyset$. Then $Y \cap X = \emptyset$ too.]

But this means that, in $\mathbb{V}^{\mathbb{P}_{\omega_2}}$, the function $\bar{\eta}^i$ exemplifies that \mathcal{D} is not an NWD ultrafilter (remember $\mathcal{D}[\mathcal{P}(\omega)]^{\mathbb{V}^{\mathbb{P}_i}} \subseteq \mathcal{D}$). Moreover, as CH implies the existence of NWD-ultrafilters, we conclude that actually $\Vdash_{\mathbb{P}_{\omega_2}} 2^{\aleph_0} = \aleph_2$.

Let us describe how one can carry out the construction. Each \mathbb{Q}_i will be $\mathbb{Q}_{I_i, h}^1$ for some increasing function $h \in {}^\omega\omega$ (e.g. $h(n) = n$) and a \mathbb{P}_i -name for a) maximal non-principal ideal I_i on ω . By 22, 17 we know that $\mathbb{Q}_{I_i, h}^1$ satisfies the demands (2)–(4) for the ultrafilter \mathcal{D}_i dual to I_i and the function $\bar{\eta}^i$ as in the proof of 22. Thus, what we have to do is to say what are the names \mathcal{D}_i . To choose them we will use the assumption of $\diamond_{\{\gamma < \omega_2 : \text{cf}(\gamma) = \omega_1\}}$. In the process of building the iteration we choose an enumeration $\langle (p_i, \tau_i) : i < \omega_2 \rangle$ of all pairs (p, τ) such that p is a condition in \mathbb{P}_{ω_2} (in its standard dense subset of size \aleph_2) and τ is a canonical (countable) \mathbb{P}_{ω_2} -name for a subset of ω . We require that $p_i \in \mathbb{P}_i$ and τ_i is a \mathbb{P}_i -name (of course, it is done by a classical bookkeeping argument). Note that each subset of $\mathcal{P}(\omega)$ from $\mathbb{V}^{\mathbb{P}_{\omega_2}}$ has a name which may be interpreted as a subset X of ω_2 : if $i \in X$ then p_i forces that τ_i is in our set. Now we may describe how we choose the names \mathcal{D}_i . By $\diamond_{\{\gamma < \omega_2 : \text{cf}(\gamma) = \omega_1\}}$ we have a sequence $\langle X_i : i < \omega_2 \ \& \ \text{cf}(i) = \omega_1 \rangle$ such that

- (i) $X_i \subseteq i$ for each $i \in \omega_2$, $\text{cf}(i) = \omega_1$,
- (ii) if $X \subseteq \omega_2$ then the set

$$\{i \in \omega_2 : \text{cf}(i) = \omega_1 \ \& \ X_i = X \cap i\}$$

is stationary.

Arriving at stage $i < \omega_2$, $\text{cf}(i) = \omega_1$ we look at the set X_i . We ask if it codes a \mathbb{P}_i -name for an ultrafilter on ω (i.e. we look at $\{(p_\alpha, \tau_\alpha) : \alpha \in X_i\}$ which may be interpreted as a \mathbb{P}_i -name for a subset of $\mathcal{P}(\omega)$). If yes, then we take this name as \mathcal{D}_i . In all remaining cases we take whatever we wish, we may even not define the name $\bar{\eta}^i$ (note: this leaves us a lot of freedom and one may use this to get some additional properties of the final model). So why we may be sure that the fifth requirement is satisfied? Suppose that we have a \mathbb{P}_{ω_2} -name for an ultrafilter on ω . This name can be thought of as a subset X of ω_2 . If $i < \omega_2$ is sufficiently closed then $X \cap i$ is a \mathbb{P}_i -name for an ultrafilter on ω which is the restriction of \mathcal{D} to $\mathbb{V}^{\mathbb{P}_i}$. So we have a club $C \subseteq \omega_2$ such that for each $i \in C$, if $\text{cf}(i) = \omega_1$ the $X \cap i$ is of this type. By (ii) the set

$$S \stackrel{\text{def}}{=} \{i < \omega_2 : i \in C \ \& \ \text{cf}(i) = \omega_1 \ \& \ X_i = X \cap i\}$$

is stationary. But easily, for each $i \in S$, the name \mathcal{D}_i has been chosen in such a way that $\mathcal{D}_i = \mathcal{D}[\mathcal{P}(\omega)]$, so we are done. ■

We note that this implies that there is also no ultrafilter with property M . This was asked by Benedikt in [Bn].

Definition 25. A non-principal ultrafilter \mathcal{D} on ω has the M -property (or property M) if:

- if for some real $\varepsilon > 0$, for $n < \omega$ we have a tree $T_n \subseteq {}^{<\omega}2$ such that $\mu(\lim(T_n)) \geq \varepsilon$
- then $(\exists A \in \mathcal{D})(\bigcap_{n \in A} \lim(T_n) \neq \emptyset)$

(where μ stands for the Lebesgue measure on ${}^\omega 2$).

Proposition 26. If a non-principal ultrafilter \mathcal{D} on ω is not NWD, then \mathcal{D} does not have the property M .

PROOF Let

$$S_\ell^\varepsilon = \{T \cap \ell \geq 2 : T \subseteq {}^{<\omega}2, T \text{ a tree not containing a cone, } \mu(\lim(T)) > \varepsilon\}$$

(note that S_ℓ^ε is a set of trees not a set of nodes) and let $S^\varepsilon = \bigcup_\ell S_\ell^\varepsilon$.

Now let $t_1 \prec t_2$ if: $t_1 \in S_{\ell_1}^\varepsilon$, $t_2 \in S_{\ell_2}^\varepsilon$, $\ell_1 < \ell_2$ and $t_1 = t_2 \cap \ell_1 \geq 2$. So S^ε is a tree with ω levels, each level is finite. As \mathcal{D} is not NWD, we can find $\eta_n^\varepsilon \in \lim(S^\varepsilon)$ for $n < \omega$ such that:

if $A \in \mathcal{D}$ then $\{\eta_n^\varepsilon : n \in A\}$ is somewhere dense.

Now let $T_n^\varepsilon \subseteq {}^{<\omega}2$ be a tree such that $\langle T_n^\varepsilon \cap \ell \geq 2 : \ell < \omega \rangle = \eta_n^\varepsilon$. We claim that:

$\langle T_n^\varepsilon : n < \omega \rangle$ exemplifies \mathcal{D} does not have the M -property.

Clearly T_n^ε is a tree of the right type, in particular

$$\mu(\lim(T_n^\varepsilon)) = \inf\{|T_n^\varepsilon \cap \ell \geq 2|/2^\ell : \ell < \omega\} \geq \varepsilon.$$

So assume $A \in \mathcal{D}$ and we are going to prove that $\bigcap_{n \in A} \lim(T_n^\varepsilon)$ is empty. We know that $\{\eta_n^\varepsilon : n \in A\}$ is somewhere dense, so there is $\ell^* < \omega$ and $t^* \in S_{\ell^*}^\varepsilon$ such that:

$$\ell^* < \ell < \omega \ \& \ t^* \prec t \in S_\ell^\varepsilon \Rightarrow (\exists n \in A)(t \triangleleft \eta_n^\varepsilon).$$

Now $\frac{|t^* \cap \ell^* \geq 2|}{2^{\ell^*}} > \varepsilon$ (so $S_{\ell^*}^\varepsilon$ was defined). So we choose $\ell > \ell^*$, such that:

- if $\nu \in \ell^* \geq 2$, $\nu \upharpoonright \ell^* \in t^*$
- then $t'_\nu = \{\rho \in \ell^* \geq 2 : \rho \upharpoonright \ell^* \in t^* \ \& \ \rho \neq \nu\} \in S_\ell^\varepsilon$,

hence there is $n = n_\nu \in A$ such that t'_ν appears in η_n^e . Now clearly

$$\begin{aligned} \bigcap_{n \in A} \text{lim}(T_n^e) &\supseteq \bigcap_{\substack{\nu \in t^* \\ \nu | t^* \in t^*}} \text{lim}(T_{n_\nu}^e) \\ &\supseteq \{\eta \in {}^\omega 2 : \eta \upharpoonright \ell \in \bigcap \{t'_\nu : \nu \in {}^\rho 2, \nu \upharpoonright \ell \in t^*\}\} = \emptyset, \end{aligned}$$

finishing the proof. ■

Conclusion 27 In the universe $V^{\mathbb{P}_{\omega_2}}$ from 24, there is no (non-principal) ultrafilter (on ω) with property M. ■

Concluding Remarks 28 We may consider some variants of $\mathbb{Q}_{I,h}^2$.

In definition 3 we have $\text{dom}(H^p)$ is as in 3(1) but: $H^p \upharpoonright B_1^p$ gives constants (not functions) and for $x_i^m \in B_3^p \setminus B_1^p$, letting $n = \min(m/E^p)$ the function $H^p(x_i^m)$ depends just on $\{x_j^n : j \leq i\}$. Moreover, it is such that changing the value of x_i^n changes the value, so $H^p(x_i^m) = f_{x_i^m}^p(x_0^n, \dots, x_{i-1}^n)$. Call this $\mathbb{Q}_{I,h}^3$.

A second variant is when we demand the functions $f_{x_i^m}^p(x_0^n, \dots, x_{i-1}^n)$ to be constant, call it $\mathbb{Q}_{I,h}^4$.

Both have the properties proved $\mathbb{Q}_{I,h}^2$. In particular, in the end of the proof of 9(5), we should change: $H^r(x_i^m)$ is defined exactly as in the proof of 9(4) except that when $i < h(n^*)$, $k = \min(m/E^p)$, $k \notin \text{dom}(E^q)$, $k \notin u$ (so m, k, n^* are E^r -equivalent) we let $H^r(x_i^m) = H^q(x_i^m) \times f(x_i^{n^*}) \times x_i^{n^*}$ (the first two are constant), so $H^r(x_i^m)$ is computed as before using this value.

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Towards Recursive Model Theory*

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Abstract. We argue that the models that are relevant to computer science are recursive and that Recursive Model Theory deserves being studied systematically, with at least the same vigor as Finite Model Theory has been. We study the status of some fundamental theorems from the classical model theory in this context and establish failure of several of them, including (generalized) Completeness, Compactness, Beth's Definability, Craig's Interpolation, and Lyndon's Lemma.

1 Introduction

Classical Model Theory deals with *all models*. If, for whatever reason, the class of models is restricted, this may potentially change model-theoretical laws that we take for granted. Take, for instance, the central for logic notion of *truth*. There may be sentences that are uniformly true in all the models of a certain class, but refutable in models not in the considered class. Hence, restricting the class of models may expand the class of true sentences. Conversely, the class of satisfiable sentences may shrink. If this actually happens, the equivalence between Model Theory and Proof Theory implied by Gödel's Completeness Theorem discontinues to hold, although in a specific situation a remedy can possibly be found by changing the axiomatization.

Recently, the Model Theory of finite models (those with finite universes) has been intensively investigated. The main motivation for Finite Model Theory has been the fact that, in several computer science applications, notably in databases, the models are often finite, and many issues in the theory of databases can be studied in the context of Finite Model Theory. Surprisingly or not, Finite Model Theory looks very much different from its classical counterpart.

The author is generally interested in Logic in Computer Science, and while finite models often are relevant to Computer Science, without question, not all the models that show up in CS applications are finite. Even in databases which have long been the Finite Model Theory refuge, infinite models not only show up, but actually move towards the central stage. In other CS playgrounds, say, in verification, finite models have never had any noticeable fraction of the market.

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hence there is $n = n_\nu \in A$ such that t'_ν appears in η_n^e . Now clearly

$$\begin{aligned} \bigcap_{n \in A} \lim(T_n^e) &\supseteq \bigcap_{\substack{\nu \in {}^{\omega}2 \\ \nu \upharpoonright t^* \in t^*}} \lim(T_{n_\nu}^e) \\ &\supseteq \{\eta \in {}^{<\omega}2 : \eta \upharpoonright \ell \in \bigcap \{t'_\nu : \nu \in {}^{\omega}2, \nu \upharpoonright \ell \in t^*\}\} = \emptyset, \end{aligned}$$

finishing the proof. ■

Conclusion 27 In the universe $V^{\mathbb{P}_{\omega_2}}$ from 24, there is no (non-principal) ultrafilter (on ω) with property M. ■

Concluding Remarks 28 We may consider some variants of $\mathbb{Q}_{I,h}^2$.

In definition 3 we have $\text{dom}(H^p)$ is as in 3(1) but: $H^p \upharpoonright B_1^p$ gives constants (not functions) and for $x_i^m \in B_3^p \setminus B_1^p$, letting $n = \min(m/E^p)$ the function $H^p(x_i^m)$ depends just on $\{x_j^n : j \leq i\}$. Moreover, it is such that changing the value of x_i^n changes the value, so $H^p(x_i^m) = f_{x_i^m}^p(x_0^n, \dots, x_{i-1}^n)$. Call this $\mathbb{Q}_{I,h}^3$.

A second variant is when we demand the functions $f_{x_i^m}^p(x_0^n, \dots, x_{i-1}^n)$ to be constant, call it $\mathbb{Q}_{I,h}^4$.

Both have the properties proved $\mathbb{Q}_{I,h}^2$. In particular, in the end of the proof of 9(5), we should change: $H^r(x_i^m)$ is defined exactly as in the proof of 9(4) except that when $i < h(n^*)$, $k = \min(m/E^p)$, $k \notin \text{dom}(E^q)$, $k \notin u$ (so m, k, n^* are E^r -equivalent) we let $H^r(x_i^m) = H^q(x_i^m) \times f(x_i^n) \times x_i^n$ (the first two are constant), so $H^r(x_i^m)$ is computed as before using this value.

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Towards Recursive Model Theory*

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Abstract. We argue that the models that are relevant to computer science are recursive and that Recursive Model Theory deserves being studied systematically, with at least the same vigor as Finite Model Theory has been. We study the status of some fundamental theorems from the classical model theory in this context and establish failure of several of them, including (generalized) Completeness, Compactness, Beth's Definability, Craig's Interpolation, and Lyndon's Lemma.

1 Introduction

Classical Model Theory deals with *all models*. If, for whatever reason, the class of models is restricted, this may potentially change model-theoretical laws that we take for granted. Take, for instance, the central for logic notion of *truth*. There may be sentences that are uniformly true in all the models of a certain class, but refutable in models not in the considered class. Hence, restricting the class of models may expand the class of true sentences. Conversely, the class of satisfiable sentences may shrink. If this actually happens, the equivalence between Model Theory and Proof Theory implied by Gödel's Completeness Theorem discontinues to hold, although in a specific situation a remedy can possibly be found by changing the axiomatization.

Recently, the Model Theory of finite models (those with finite universes) has been intensively investigated. The main motivation for Finite Model Theory has been the fact that, in several computer science applications, notably in databases, the models are often finite, and many issues in the theory of databases can be studied in the context of Finite Model Theory. Surprisingly or not, Finite Model Theory looks very much different from its classical counterpart.

The author is generally interested in Logic in Computer Science, and while finite models often are relevant to Computer Science, without question, not all the models that show up in CS applications are finite. Even in databases which have long been the Finite Model Theory refuge, infinite models not only show up, but actually move towards the central stage. In other CS playgrounds, say, in verification, finite models have never had any noticeable fraction of the market.

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