# A model in which the Separation principle holds for a given effective projective Sigma-class* 

Vladimir Kanovei ${ }^{\dagger} \quad$ Vassily Lyubetsky ${ }^{\ddagger}$

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#### Abstract

In this paper, we prove the following: If $n \geq 3$, there is a generic extension of $\mathbf{L}$ - the constructible universe - in which it is true that the Separation principle holds for both effective (lightface) classes $\Sigma_{n}^{1}$ and $\Pi_{n}^{1}$ of sets of integers. The result was announced long ago by Leo Harrington with a sketch of the proof for $n=3$; its full proof has never been presented. Our methods are based on a countable product of almost-disjoint forcing notions independent in the sense of Jensen-Solovay.


## 1 Introduction

The separation problem was introduced in descriptive set theory by Luzin [21. In modern terms, the separation principle - or simply Separation, for a given projective (boldface) class $\boldsymbol{\Sigma}_{n}^{1}$ or $\boldsymbol{\Pi}_{n}^{1}$ - is the assertion that

Boldface Separation for $\boldsymbol{\Sigma}_{n}^{1}$ or $\boldsymbol{\Pi}_{n}^{1}$ : any pair of disjoint $\boldsymbol{\Sigma}_{n}^{1}$, resp, $\boldsymbol{\Pi}_{n}^{1}$ sets $X, Y$ of reals can be separated by a $\boldsymbol{\Delta}_{n}^{1}$ set.

Accordingly, the classical separation problem is a question of whether Boldface Separation holds for this or another projective class $\boldsymbol{\Sigma}_{n}^{1}$ or $\boldsymbol{\Pi}_{n}^{1}$. Luzin and then Novikov [28] underlined the importance and difficulty of this problem. (See [25, 19, [18] for details and further references.)

Luzin [22, 21] and Novikov [26] proved that Boldface Separation holds for $\boldsymbol{\Sigma}_{1}^{1}$ but fails for the dual class $\boldsymbol{\Pi}_{1}^{1}$. Somewhat later, it was established by Novikov [27] that the picture changes at the next projective level: Boldface Separation holds for $\boldsymbol{\Pi}_{2}^{1}$ but fails for $\boldsymbol{\Sigma}_{2}^{1}$.

As for the higher levels of projective hierarchy, all attempts made in classical descriptive set theory to solve the separation problem above the second level did

[^0]not work, until some additional set theoretic axioms were introduced-in particular, those by Novikov [28] and Addison [2, 1]. Gödel's axiom of constructibility $\mathbf{V}=\mathbf{L}$ implies that, for any $n \geq 3$, Boldface Separation holds for $\boldsymbol{\Pi}_{n}^{1}$ but fails for $\boldsymbol{\Sigma}_{n}^{1}$ pretty similar to second level.

In such a case, it is customary in modern set theory to look for models in which the separation problem is solved differently than under $\mathbf{V}=\mathbf{L}$ for at least some projective classes $\boldsymbol{\Sigma}_{n}^{1}$ and $\boldsymbol{\Pi}_{n}^{1}, n \geq 3$. This goal is split into two different tasks:
(I) Prove the independence of the $\Pi$-side Boldface Separation - that is, given $n \geq 3$, find models in which Boldface Separation fails for the class $\Pi_{n}^{1}$;
(II) Prove the consistency of the $\Sigma$-side Boldface Separation-that is, given $n \geq$ 3 , find models in which Boldface Separation holds for the class $\boldsymbol{\Sigma}_{n}^{1}$.

As for models, we focus here only on generic extensions of the constructible universe $\mathbf{L}$. Other set theoretic models, e.g., those based on strong determinacy or large cardinal hypotheses, are not considered in this paper. (We may only note in brackets that, by Addison and Moschovakis [3], and Martin [23], the axiom of projective determinacy $\mathbf{P D}$ implies that, for any $m \geq 1$, the separation problem is solved affirmatively for $\boldsymbol{\Sigma}_{2 m+1}^{1}$ and $\boldsymbol{\Pi}_{2 m+2}^{1}$ and negatively for $\boldsymbol{\Pi}_{2 m+1}^{1}$ and $\boldsymbol{\Sigma}_{2 m+2}^{1}$ - similar to what happens at the first and second level corresponding to $n=0$ in this scheme. See also Steel [29, 30], and Hauser and Schindler [9] for some other relevant results.).

Problems (I) and (II) have been well-known since the early years of forcing, e.g., see problem P3030, and especially P3029 ( $=(\mathrm{II})$ for $n=3$ ) in a survey [24] by Mathias.

Two solutions for part (I) are known so far. Harrington's two-page handwritten note ([Addendum A1] [8]) contains a sketch of a model, without going into details, defined by the technique of almost-disjoint forcing of Solovay and Jensen [11], in which indeed Separation fails for both $\boldsymbol{\Sigma}_{n}^{1}$ and $\boldsymbol{\Pi}_{n}^{1}$ for a given $n$. This research was cited in Moschovakis [25] (Theorem 5B.3), and Mathias [24 (Remark P3110 on page 166), but has never been published or otherwise detailed in any way. Some other models, with the same property of failure of Separation for different projective classes, were recently defined and studied in [12, 18].

As for (II), the problem as it stands is open so far, and no conclusive achievement, such as a model (a generic extension of $\mathbf{L}$ ) in which Boldface Separation holds for $\boldsymbol{\Sigma}_{n}^{1}$ for some $n \geq 3$, is known. Yet, the following modification turns out to be easier to work with. The effective or lightface Separation, for a given lightface class $\Sigma_{n}^{1}$ or $\Pi_{n}^{1}$ (we give [25] as a reference on the lightface projective hierarchy), is the assertion that

Lightface Separation for $\Sigma_{n}^{1}$ or $\Pi_{n}^{1}$ : any pair of disjoint $\Sigma_{n}^{1}$, respectively, $\Pi_{n}^{1}$ sets $X, Y$ can be separated by a $\Delta_{n}^{1}$ set-here, unlike the Boldface Separation case, the sets $X, Y$ can be either sets of reals or sets of integers.

Accordingly, the effective or lightface separation problem is a question of whether Lightface Separation holds for this or another class of the form $\Sigma_{n}^{1}$ or $\Pi_{n}^{1}$, with specific versions for sets of reals and sets of integers. Addison [2, (1) demonstrated that, similar to the above, Lightface Separation holds for $\Sigma_{1}^{1}$ and $\Pi_{2}^{1}$; fails for $\Pi_{1}^{1}$ and $\Sigma_{2}^{1}$; and under the axiom of constructibility $\mathbf{V}=\mathbf{L}$, it holds for $\Pi_{n}^{1}$ and fails for $\Sigma_{n}^{1}$ for all $n \geq 3$-both in the "real" and the "integer" versions. (See also [25].)

In this context, Harrington announced in [8] that there is a model in which Lightface Separation holds both for the class $\Sigma_{3}^{1}$ for sets of integers, and for the class $\Pi_{3}^{1}$ for sets of integers. A two-page handwritten sketch of a construction of such a model is given in ([Addendum A3] [8]) without much elaboration of arguments. The goal of this paper is to prove the next theorem, which generalizes the cited Harrington result and thereby is a definite advance in the direction of (II) in the context of Lightface Separation for sets of integers. This is the main result of this paper.
Theorem 1.1. Let $\llbracket \geq 2$. There is a generic extension of $\mathbf{L}$ in which
(i) Lightface Separation holds for $\Sigma_{n+1}^{1}$ sets of integers, so that any pair of disjoint $\Sigma_{n+1}^{1}$ sets $X, Y \subseteq \omega$ can be separated by a $\Delta_{n+1}^{1}$ set;
(ii) Lightface Separation also holds for $\Pi_{\mathfrak{m}+1}^{1}$ sets of integers, so that any pair of disjoint $\Pi_{\mathrm{m}+1}^{1}$ sets $X, Y \subseteq \omega$ can be separated by a $\Delta_{\mathfrak{m}+1}^{1}$ set.

Our proof of this theorem will follow a scheme that includes both some arguments outlined by Harrington in [8], Addendum A3 (mainly related to the most elementary case $n=2$ ) and some arguments absent in [8], in particular, those related to the generalization to the case $n \geq 3$. (We may note here that $[8$ is neither a beta-version of a paper, nor a preprint of any sort, but rather handwritten notes to a talk in which omissions of even major details can be expected.) All this will require both a fairly sophisticated construction of the model itself and a fairly complex derivation of its required properties by rather new methods for modern set theoretic research. Thus, we are going to proceed with filling-in all necessary details left aside in [8]. We hope that the detailed acquaintance with the set theoretic methods first introduced by Harrington will serve to the benefits of the reader envisaged.

To prove Theorem 1.1, we make use of a generic extension of $\mathbf{L}$ defined in our earlier paper [17] (and before that in [8]-modulo some key details absent in [8) in order to prove the consistency of the equality $\mathscr{P}(\omega) \cap \mathbf{L}=\mathscr{P}(\omega) \cap \Delta_{\mathrm{m}+1}^{1}$ for a given $n \geq 2$. (The equality claims that the constructible reals are the same as $\Delta_{\mathfrak{m}+1}^{1}$ reals. Its consistency was a major problem posed by Harvey Friedman [6].) We present the construction of this generic model in all necessary detail.

This includes a version of almost-disjoint forcing considered in Section 2 the cone-homogeneity lemma in Section 3, the systems and product forcing construction in Section [4, and a Jensen-Solovay-style construction of the actual countable support forcing product $\mathbb{Q}$ in Section 5. Theorem 5.1 and Definition 5.2 in Section 5 present the construction of $\mathbb{Q}$ in $\mathbf{L}$ via the union of a $2^{\omega}$-long increasing
sequence of systems $\mathbb{U}_{\xi}, \xi<\omega_{2}$, which satisfies suitable completeness and definability requirements (that depend on the choice of the value of an integer $n$ as in Theorem (1.1), and also follows the Jensen-Solovay idea of Cohen-generic extensions at each step $\xi<\omega_{2}$ of the inductive construction of $\mathbb{U}_{\xi}$.

Then, we consider corresponding $\mathbb{Q}$-generic extensions $\mathbf{L}[G]$ in Section 6, and their subextensions involved in the proof of Theorem[1.1]in Section7(Theorem[7.1). Two key lemmas are established in Section 8, and the proof of theorems 7.1 and 1.1 is finalized in Section 9 (the $\Sigma_{\mathrm{m}+1}^{1}$ case) and in Section 10 (the $\Pi_{\mathrm{m}+1}^{1}$ case).

The final section on conclusions and discussion completes the paper.

## 2 Almost-disjoint forcing

Almost-disjoint forcing was invented by Jensen and Solovay [11]. Here, we make use of a $\omega_{1}$-version of this tool considered in ([Section 5] [11]). The version we utilize here exactly corresponds to the case $\Omega=\omega_{1}^{\mathrm{L}}$ developed in our earlier paper [17] (and to less extent in [16]). This will allow us to skip some proofs below. Assume the following:

- $\Omega=\omega_{1}^{\mathrm{L}}$, the first uncountable ordinal in $\mathbf{L}$.
- Fun $=\left(\Omega^{\Omega}\right) \cap \mathbf{L}=$ all $\Omega$-sequences of ordinals $<\Omega$ in $\mathbf{L}$.
- Seq $=(\Omega<\Omega \backslash\{\Lambda\}) \cap \mathbf{L}$ is the set of all sequences $s \in \mathbf{L}$ of ordinals $<\Omega$, of length $0<\operatorname{lh} s<\Omega$.

By definition, the sets Fun, Seq belong to $\mathbf{L}$ and $\operatorname{card}(\mathbf{S e q})=\Omega=\omega_{1}^{\mathbf{L}}$ whereas $\operatorname{card}($ Fun $)=\omega_{2}^{\mathbf{L}}$ in $\mathbf{L}$. Note that $\Lambda$, the empty sequence, does not belong to Seq.

- A set $X \subseteq$ Fun is dense iff for any $s \in \mathbf{S e q}$ there is $f \in X$ such that $s \subset f$.
- If $S \subseteq$ Seq, $f \in$ Fun; then, let $S / f=\{\xi<\Omega: f \upharpoonright \xi \in S\}$.
- If $S / f$ is unbounded in $\Omega$, then say that $S$ covers $f$; otherwise, $S$ does not cover $f$.

The general goal of the almost-disjoint forcing is the following: given a set $u \subseteq$ Fun in the ground set universe $\mathbf{L}$, find a generic set $S \subseteq$ Seq such that the equivalence " $f \in u \Longleftrightarrow S$ does not cover $f$ " holds for each $f \in$ Fun in the ground universe.

Definition 2.1. $Q^{*}$ is the set of all pairs $p=\left\langle S_{p} ; F_{p}\right\rangle \in \mathbf{L}$ of finite sets $F_{p} \subseteq$ Fun, $S_{p} \subseteq$ Seq. Note that $Q^{*} \in \mathbf{L}$. Elements of $Q^{*}$ are called (forcing) conditions.

If $p \in Q^{*}$, then put $F_{p}^{\vee}=\left\{f \upharpoonright \xi: f \in F_{p} \wedge 1 \leq \xi<\Omega\right\}$,; this is a tree in Seq.
Let $p, q \in Q^{*}$. Define $q \leqslant p$ (that is, $q$ is stronger as a forcing condition) iff $S_{p} \subseteq S_{q}, F_{p} \subseteq F_{q}$, and the difference $S_{q} \backslash S_{p}$ does not intersect $F_{p}^{\vee}$, i.e., $S_{q} \cap F_{p}^{\vee}=$ $S_{p} \cap F_{p}^{\vee}$. Clearly, we have $q \leqslant p$ iff $S_{p} \subseteq S_{q}, F_{p} \subseteq F_{q}$, and $S_{q} \cap F_{p}^{\vee}=S_{p} \cap F_{p}^{\vee}$.

If $u \subseteq$ Fun, then put $Q[u]=\left\{p \in Q^{*}: F_{p} \subseteq u\right\}$.

Lemma 2.2 (Lemma 1 in [17]). Conditions $p, q \in Q^{*}$ are compatible in $Q^{*}$ iff (1) $S_{q} \backslash S_{p}$ does not intersect $F_{p}^{\vee}$, and (2) $S_{p} \backslash S_{q}$ does not intersect $F_{q}^{\vee}$.

Thus, any conditions $p, q \in Q[u]$ are compatible in $Q[u]$ iff $p, q$ are compatible in $Q^{*}$ iff the condition $p \wedge q=\left\langle S_{p} \cup S_{q} ; F_{p} \cup F_{q}\right\rangle \in Q[u]$ satisfies $p \wedge q \leqslant p$ and $p \wedge q \leqslant q$.

## 3 The almost-disjoint forcing notions are homogeneous

We are going to show that forcing notions of the form $Q[u]$ are sufficiently homogeneous. This is not immediately clear here, unlike the case of many other homogeneity claims. Assume that conditions $p, q \in Q^{*}$ satisfy the next requirement:

$$
\begin{equation*}
F_{p}=F_{q} \quad \text { and } \quad S_{p} \cup S_{q} \subseteq F_{p}^{\vee}=F_{q}^{\vee} . \tag{1}
\end{equation*}
$$

Then, a transformation $h_{p q}$ acting on conditions is defined as follows.
If $p=q$, then define $h_{p q}(r)=r$ for all $r \in Q^{*}$, the identity.
Suppose that $p \neq q$. Then, $p, q$ are incompatible by (1) and Lemma 2.2, Define $d_{p q}=\left\{r \in Q^{*}: r \leqslant p \vee r \leqslant q\right\}$, the domain of $h_{p q}$. Let $r \in d_{p q}$. We put $h_{p q}(r)=r^{\prime}:=\left\langle S_{r^{\prime}}, F_{r^{\prime}}\right\rangle$, where $F_{r^{\prime}}=F_{r}$ and

$$
S_{r^{\prime}}=\left\{\begin{array}{lll}
\left(S_{r} \backslash S_{p}\right) \cup S_{q} & \text { in case } & r \leqslant p,  \tag{2}\\
\left(S_{r} \backslash S_{q}\right) \cup S_{p} & \text { in case } & r \leqslant q .
\end{array}\right.
$$

In this case, the difference between $S_{r}$ and $S_{r^{\prime}}$ is located within the set $X=$ $F_{p}^{\vee}=F_{q}^{\vee}$, so that $S_{r} \cap X=S_{p}$ and $S_{r^{\prime}} \cap X=S_{q}$ whenever $r \leqslant p$, while $S_{r} \cap X=S_{q}$ and $S_{r^{\prime}} \cap X=S_{p}$ whenever $r \leqslant q$. The next lemma is Lemma 6 in [17].

Lemma 3.1. (i) If $u \subseteq$ Fun is dense and $p_{0}, q_{0} \in Q[u]$, then there exist conditions $p, q \in Q[u]$ with $p \leqslant p_{0}, q \leqslant q_{0}$, satisfying (1).
(ii) Let $p, q \in Q^{*}$ satisfy (1). If $p=q$, then $h_{p q}$ is the identity transformation. If $p \neq q$, then $h_{p q}$ is an order automorphism of $d_{p q}=\left\{r \in Q^{*}: r \leqslant p \vee r \leqslant q\right\}$, satisfying $h_{p q}(p)=q$ and $h_{p q}=\left(h_{p q}\right)^{-1}=h_{q p}$.
(iii) If $u \subseteq$ Fun and $p, q \in Q[u]$ satisfy (11), then $h_{p q}$ maps the set $Q[u] \cap d_{p q}$ onto itself order-preserving.

Proof (sketch). (i) By the density of $u$, there is a countable set $F \subseteq$ Fun satisfying $F_{p} \cup F_{q} \subseteq F$ and $S_{p} \cup S_{q} \subseteq F^{\vee}=\{f \upharpoonright \xi: f \in F \wedge 1 \leq \xi<\Omega\}$. Put $p=\left\langle S_{p}, F\right\rangle$ and $q=\left\langle S_{q}, F\right\rangle$. Claims (ii) and (iii) are routine.

Corollary 3.2 (in $\mathbf{L}$ ). If a set $u \subseteq$ Fun is dense, then $Q[u]$ is cone homogeneous in the sense of [5], i.e., if $p_{0}, q_{0} \in Q[u]$, then there exist conditions $p, q \in Q[u]$ with $p \leqslant p_{0}, q \leqslant q_{0}$, such that the cones $Q[u]_{\leqslant p}=\left\{p^{\prime} \in Q[u]: p^{\prime} \leqslant p\right\}$ and $Q[u]_{\leqslant q}$ are order-isomorphic.

## 4 Systems and product almost-disjoint forcing

To prove Theorem 1.1, we make use of a forcing notion equal to the countablesupport product of a collapse forcing $\mathbb{C}$ and $\omega_{2}^{\mathrm{L}}$-many forcing notions of the form $Q[u], u \subseteq$ Fun .

We work in L. Define $\mathbb{C}=\mathscr{P}(\omega) \cap \mathbf{L}^{<\omega}$, the set of all finite sequences of subsets of $\omega$ in $\mathbf{L}$, an ordinary forcing $\mathscr{P}(\omega) \cap \mathbf{L}$ to collapse down to $\omega$.

Let $\mathcal{I}=\omega_{2}^{\mathbf{L}}$ and $\mathcal{I}^{+}=\mathcal{I} \cup\{-1\}$, the index set of the mentioned product. Let a system be any map $U:|U| \rightarrow \mathscr{P}$ (Fun) such that $|U| \subseteq \mathcal{I}$, each set $U(\nu)(\nu \in|U|)$ is dense in Fun, and the components $U(\nu) \subseteq$ Fun $(\nu \in|U|)$ are pairwise disjoint.

Given a system $U$ in $\mathbf{L}$, we let $\mathbf{Q}[U]$ be the finite-support product of $\mathbb{C}$ and the sets $Q[U(\nu)], \nu \in|U|$. That is, $\mathbf{Q}[U]$ consists of all maps $p$ defined on a finite set $\operatorname{dom} p=|p|^{+} \subseteq|U| \cup\{-1\}$ so that $p(\nu) \in Q[U(\nu)]$ for all $\nu \in|p|:=|p|^{+} \backslash\{-1\}$, and if $-1 \in|p|^{+}$, then $\boldsymbol{b}_{p}:=p(-1) \in \mathbb{C}$. If $p \in \mathbf{Q}[U]$, then put $F_{p}(\nu)=F_{p(\nu)}$ and $S_{p}(\nu)=S_{p(\nu)}$ for all $\nu \in|p|$, so that $p(\nu)=\left\langle S_{p}(\nu) ; F_{p}(\nu)\right\rangle$.

We order $\mathbf{Q}[U]$ component-wise: $p \leqslant q$ ( $p$ is stronger as a forcing condition) iff $|q|^{+} \subseteq|p|^{+}, \boldsymbol{b}_{q} \subseteq \boldsymbol{b}_{p}$ in case $-1 \in|q|^{+}$, and $p(\nu) \leqslant q(\nu)$ in $Q[U(\nu)]$ for all $\nu \in|q|$. Note that $\mathbf{Q}[U]$ contains the empty condition $\odot \in \mathbf{Q}[U]$ satisfying $|\odot|^{+}=\varnothing$; obviously, $\odot$ is the $\leqslant$-least (and weakest as a forcing condition) element of $\mathbf{Q}[U]$.

Lemma 4.1 (in $\mathbf{L}$ ). If $U$ is a system, then the forcing notion $\mathbf{Q}[U]$ satisfies $\omega_{2}^{\mathbf{L}}$ $C C$.

Proof. We argue in $\mathbf{L}$. Assume towards the contrary that $X \subseteq \mathbf{Q}[U]$ is an antichain of cardinality card $X=\omega_{2}$. As $\operatorname{card} \mathbb{C}=\omega_{1}$, we can assume that $\boldsymbol{b}_{p}=\boldsymbol{b}_{q}$ for all $p, q \in X$. Consider the set $S=\{|p|: p \in X\}$; it consists of finite subsets of $\omega_{2}$.

Case 1: card $S \leq \omega_{1}$. Then, by the cardinality argument, there is a set $X^{\prime} \subseteq X$ and some $a \in S$ such that $|p|=a$ for all $p \in X^{\prime}$ and still card $X^{\prime}=\omega_{2}$. Note that if $p \neq q$ belongs to $X^{\prime}$, then $\boldsymbol{b}_{p}=\boldsymbol{b}_{q}$ by the above; therefore, as $p, q$ are incompatible, we have $S_{p} \neq S_{q}$. Thus, $P=\left\{S_{p}: p \in X^{\prime}\right\}$ still satisfies card $P=\omega_{2}$. This is a contradiction since obviously the set $\left\{S_{p}: p \in \mathbf{Q}[U] \wedge|p|=a\right\}$ has cardinality $\omega_{1}$.

Case 2: card $S=\omega_{2}$. Then, by the $\Delta$-system lemma (see e.g. Lemma 111.2.6 in Kunen [20]) there is a set $S^{\prime} \subseteq S$ and a finite set $\delta \subseteq \omega_{2}$ (the root) such that $a \cap b=\delta$ for all $a \neq b$ in $S^{\prime}$, and still card $S^{\prime}=\omega_{2}$. For any $a \in S$, pick a condition $p_{a} \in X^{\prime}$ with $|p|=a$; then, $X^{\prime \prime}=\left\{p_{a}: a \in S^{\prime}\right\}$ still satisfies card $X^{\prime \prime}=\omega_{2}$. By construction, if $p \neq q$ belong to $X^{\prime \prime}$, then $|p| \cap|q|=\delta$ and $p, q$ are incompatible; hence, the restricted conditions $p \upharpoonright \delta, q \upharpoonright \delta$ are incompatible as well. Thus, the set $Y=\left\{p \upharpoonright \delta: p \in X^{\prime \prime}\right\}$ still has cardinality card $Y=\omega_{2}$ and is an antichain. On the other hand, $|q|=\delta$ for all $q \in Y$. Thus we have a contradiction as in Case 1.

## 5 Jensen-Solovay construction

Our plan is to define a system $\mathbb{U} \in \mathbf{L}$ such that any $\mathbf{Q}[\mathbb{U}]$-generic extension of $\mathbf{L}$ has a subextension that witnesses Theorem 1.1. Such a system will be defined
in the form of a component-wise union of a $\omega_{2}^{\mathbf{L}}$-long increasing sequence of small systems, where the smallness means that, in $\mathbf{L}$, the system involves only $\omega_{1}^{\mathbf{L}}$-many functions in Fun.

## We work in $L$.

- A system $U$ is small, if both the set $|U|$ and each set $U(\nu)(\nu \in|U|)$ has cardinality $\leq \omega_{1}^{\mathbf{L}}$.
- If $U, V$ are systems, $|U| \subseteq|V|$, and $U(\nu) \subseteq V(\nu)$ for all $\nu \in|U|$, then say that $V$ extends $U$, in symbol $U \preccurlyeq V$.
- If $\left\{U_{\xi}\right\}_{\xi<\lambda}$ is a $\preccurlyeq$-increasing sequence of systems, then define a system $U=$ $\bigvee_{\xi<\lambda} U_{\xi}$ by $|U|=\bigcup_{\xi<\lambda}\left|U_{\xi}\right|$ and $U(\nu)=\bigcup_{\xi<\lambda, \nu \in\left|U_{\xi}\right|} U_{\xi}(\nu)$ for all $\nu \in|U|$.

We let $\mathbf{Z F C}^{-}$be ZFC minus the Power Set axiom, with the schema of Collection instead of Replacement, with AC in the form of the well-orderability principle, and with the axiom: " $\omega_{1}$ exists". See [7] on versions of ZFC sans the Power Set axiom in detail. Let $\mathbf{Z F C}_{2}^{-}$be $\mathbf{Z F C}^{-}$plus the axioms: $\mathbf{V}=\mathbf{L}$, and the axiom "every set $x$ satisfies card $x \leq \omega_{1}$ ".

Let $U, V$ be systems. Suppose that $M$ is any transitive model of $\mathbf{Z F C}_{2}^{-}$containing $\Omega$. Define $U \preccurlyeq_{M} U^{\prime}$ iff $U \preccurlyeq U^{\prime}$ and the following holds:
(a) the set $\Delta\left(U, U^{\prime}\right)=\bigcup_{\nu \in|U|}\left(U^{\prime}(\nu) \backslash U(\nu)\right)$ is multiply Seq-generic over $M$, in the sense that every sequence $\left\langle f_{1}, \ldots f_{m}\right\rangle$ of pairwise different functions $f_{\ell} \in \Delta\left(U, U^{\prime}\right)$ is generic over $M$ in the sense of $\mathbf{S e q}=\omega_{1}{ }^{<\omega_{1}}$ as the forcing notion in $\mathbf{L}$, and
(b) if $\nu \in|U|$, then the set $U^{\prime}(\nu) \backslash U(\nu)$ is dense in Fun, and therefore uncountable.

Note a corollary of (a) $\Delta\left(U, U^{\prime}\right) \cap M=\varnothing$.

- Let JS, Jensen-Solovay pairs, be the set of all pairs $\langle M, U\rangle$, where $M \models$ $\mathbf{Z F C}_{2}^{-}$is a transitive model containing $\Omega$ and $U \in M$ is a system. Then, the sets Seq, $\mathbf{Q}[U]$ also belong to $M$.
- Let sJS, small Jensen-Solovay pairs, be the set of all pairs $\langle M, U\rangle \in \mathbf{J S}$ such that $U$ is a small system in the sense above and $\operatorname{card} M \leq \omega_{1}$ (in $\mathbf{L}$ ).
- $\langle M, U\rangle \preccurlyeq\left\langle M^{\prime}, U^{\prime}\right\rangle\left(\left\langle M^{\prime}, U^{\prime}\right\rangle\right.$ extends $\left.\langle M, U\rangle\right)$ iff $M \subseteq M^{\prime}$ and $U \preccurlyeq M U^{\prime}$; $\langle M, U\rangle \prec\left\langle M^{\prime}, U^{\prime}\right\rangle$ (strict) iff $\langle M, U\rangle \preccurlyeq\left\langle M^{\prime}, U^{\prime}\right\rangle$ and $\forall \nu \in|U|\left(U(\nu) \varsubsetneqq U^{\prime}(\nu)\right)$.
- A Jensen-Solovay sequence of length $\lambda \leq \Omega^{\oplus}=\omega_{2}$ is any strictly $\prec-$ increasing $\lambda$-sequence $\left\{\left\langle M_{\xi}, U_{\xi}\right\rangle\right\}_{\xi<\lambda}$ of pairs $\left\langle M_{\xi}, U_{\xi}\right\rangle \in \mathbf{s J S}$, satisfying $U_{\eta}=\bigvee_{\xi<\eta} U_{\xi}$ on limit steps. Let $\overrightarrow{\mathbf{J S}}_{\lambda}$ be the set of all such sequences.
- A pair $\langle M, U\rangle \in \mathbf{s J S}$ solves a set $D \subseteq \mathbf{s J S}$ iff either $\langle M, U\rangle \in D$ or there is no pair $\left\langle M^{\prime}, U^{\prime}\right\rangle \in D$ that extends $\langle M, U\rangle$.
- Let $D^{\text {solv }}$ be the set of all pairs $\langle M, U\rangle \in \mathbf{s J S}$, which solve a given set $D \subseteq \mathbf{s J S}$.
- Let $n \geq 3$. A sequence $\left\{\left\langle M_{\xi}, U_{\xi}\right\rangle\right\}_{\xi<\omega_{2}} \in \overrightarrow{\mathbf{J}}_{\omega_{2}}$ is $n$-complete iff it intersects every set of the form $D^{\text {solv }}$, where $D \subseteq \mathbf{s J S}$ is a $\Sigma_{n-2}^{\mathrm{H} \omega_{2}}\left(\mathrm{H} \omega_{2}\right)$ set.

If $\kappa$ is a cardinal then $\mathrm{H} \kappa$ is the collection of all sets $x$ whose transitive closure $\mathrm{TC}(x)$ has cardinality $\operatorname{card}(\mathrm{TC}(x))<\kappa$. Arguing in $\mathbf{L}$, we have $\mathrm{H} \omega_{2}=\mathbf{L}_{\omega_{2}}$, of course.

Further, $\Sigma_{n-2}^{\mathrm{H} \omega_{2}}\left(\mathrm{H} \omega_{2}\right)$ means definability by a $\Sigma_{n-2}$ formula of the $\in$-language, in which any definability parameters in $\mathrm{H} \omega_{2}$ are allowed, while $\Sigma_{n-2}^{\mathrm{H} \omega_{2}}$ means the parameter-free definability. Similarly, $\Delta_{n-1}^{\mathrm{H} \omega_{2}}(\{\Omega\})$ in the next theorem means that $\Omega=\omega_{1}^{\mathrm{L}}$ is allowed as a sole parameter. It is a simple exercise that sets $\{\mathbf{S e q}\}$ and Seq are $\Delta_{1}^{\mathrm{H} \omega_{2}}(\{\Omega\})$ under $\mathbf{V}=\mathbf{L}$. To account for $\Omega$ as a parameter, note that the set $\omega_{1}$ is $\Sigma_{1}^{\mathrm{H} \omega_{2}}$; hence, the singleton $\left\{\omega_{1}\right\}$ is $\Delta_{2}^{\mathrm{H} \omega_{2}}$.

Generally, we refer to, e.g., 44, Part B, 5.4, or [10], Chap. 13, on the Lévy hierarchy of $\in$-formulas and definability classes $\Sigma_{n}^{H}, \Pi_{n}^{H}, \Delta_{n}^{H}$ for any transitive set $H$.

Theorem 5.1 (Theorem 3 in (17). It is true in $\mathbf{L}$ that if $n \geq 2$, then there is a sequence $\left\{\left\langle M_{\xi}, U_{\xi}\right\rangle\right\}_{\xi<\omega_{2}} \in \overrightarrow{\mathbf{J}}_{\omega_{2}}$ of class $\Delta_{n-1}^{\mathrm{H} \omega_{2}}(\{\Omega\})$; hence, $\Delta_{n-1}^{\mathrm{H} \omega_{2}}$ in case $n \geq 3$, and in addition $n$-complete in case $n \geq 3$, such that $\xi \in\left|U_{\xi+1}\right|$ for all $\xi<\omega_{2}$.

Similar theorems were established in [13, 14, 15] for different purposes.
Definition 5.2 (in L). Fix a number $n \geq 2$ during the proof of Theorem 1.1, Let $\left\{\left\langle M_{\xi}, \mathbb{U}_{\xi}\right\rangle\right\}_{\xi<\omega_{2}} \in \overrightarrow{\mathbf{J S}}_{\omega_{2}}$ be a Jensen-Solovay sequence as in Thm 5.1, thus
(i) the sequence is of class $\Delta_{m-1}^{\mathrm{H} \omega_{2}}$;
(ii) we have $\xi \in\left|\mathbb{U}_{\xi+1}\right|$ for all $\xi$;
(iii) if $n \geq 3$, then the sequence is $n$-complete.

Put $\mathbb{U}=\bigvee_{\xi<\omega_{2}} \mathbb{U}_{\xi}$, so $\mathbb{U}(\nu)=\bigcup_{\xi<\omega_{2}, \nu \in\left|\mathbb{U}_{\xi}\right|} \mathbb{U}_{\xi}(\nu)$ for all $\nu \in \mathcal{I}$. Thus, $\mathbb{U} \in \mathbf{L}$ is a system and $|\mathbb{U}|=\mathcal{I}$ since $\xi \in\left|\mathbb{U}_{\xi+1}\right|$ for all $\xi$.

We define $\mathbb{Q}=\mathbf{Q}[U]$ (the basic forcing notion). Thus, $\mathbb{Q} \in \mathbf{L}$ is the finitesupport product of the set $\mathbb{C}$ and sets $\mathbb{Q}(\nu)=Q[\mathbb{U}(\nu)], \nu \in \mathcal{I}$.
Lemma 5.3 (in $\mathbf{L})$. The binary relation $f \in \mathbb{U}(\nu)$ is $\Delta_{m-1}^{\mathrm{H} \omega_{2}}(\{\Omega\})$.
Proof. To get a $\Sigma$ definition, make use of (i)] of Definition 5.2. To get a $\Pi$ definition, note that, in $\mathbf{L}, f \in \mathbb{U}(\nu)$ iff for any $\xi<\omega_{2}$, if $f \in \mathbb{M}_{\xi}$ and $\nu<\xi$ then $f \in \mathbb{U}_{\xi}(\nu)$.

## 6 Basic generic extension

We consider $\mathbb{Q}_{\mathrm{n}}:=\mathbb{Q}_{\mathrm{n}}=\mathbf{Q}[\mathbb{U}]$ (see Definition [5.2) as a forcing notion in $\mathbf{L}$. Accordingly, we will study $\mathbb{Q}$-generic extensions $\mathbf{L}[G]$ of the ground universe $\mathbf{L}$. Define some elements of these extensions. Suppose that $G \subseteq \mathbb{Q}$. Let

$$
\boldsymbol{b}_{G}=\bigcup_{p \in G} \boldsymbol{b}_{p}, \quad \text { and } \quad S_{G}(\nu)=S_{G(\nu)}=\bigcup_{p \in G} S_{p}(\nu)
$$

for any $\nu \in|G|$, where $G(\nu)=\{p(\nu): p \in G\} \subseteq Q[\mathbb{U}(\nu)]$. Thus, $S_{G}(\nu) \subseteq$ Seq.
Therefore, any $\mathbb{Q}$-generic set $G \subseteq \mathbb{Q}$ splits into the family of sets $G(\nu), \nu \in \mathcal{I}$, and a separate $\operatorname{map} \boldsymbol{b}_{G}: \omega \xrightarrow{\text { onto }} \mathscr{P}(\omega) \cap \mathbf{L}$. It follows from Lemma4.1 by standard arguments that $\mathbb{Q}$-generic extensions of $\mathbf{L}$ satisfy $\omega_{1}=\omega_{2}^{\mathbf{L}}$.

Lemma 6.1 (Lemma 9 in [17). Let $G \subseteq \mathbb{Q}$ be a set $\mathbb{Q}$-generic over $\mathbf{L}$. Then,
(i) $\boldsymbol{b}_{G}$ is a $\mathbb{C}$-generic map from $\omega$ onto $\mathscr{P}(\omega) \cap \mathbf{L}$;
(ii) if $\nu \in \mathcal{I}$, then the set $G(\nu)=\{p(\nu): p \in G\} \in \mathbf{L}[G]$ is $P[\mathbb{U}(\nu)]$-generic over $\mathbf{L}$ - hence, if $f \in \mathbf{F u n}$, then $f \in \mathbb{U}(\nu)$ iff $S_{G}(\nu)$ does not cover $f$.

Now suppose that $c \subseteq \mathcal{I}^{+}$. If $p \in \mathbb{Q}$, then a restriction $p^{\prime}=p \upharpoonright c \in \mathbb{Q}$ is defined by $\left|p^{\prime}\right|=c \cap|p|$ and $p^{\prime}(\nu)=p(\nu)$ for all $\nu \in\left|p^{\prime}\right|$. In particular, if $\nu \in \mathcal{I}^{+}$, then let

$$
\left.p \upharpoonright_{\neq \nu}=p \upharpoonright\left(|p|^{+} \backslash\{\nu\}\right) \quad \text { and } \quad p \upharpoonright_{\nu}=p \upharpoonright\{\nu\} \quad \text { (identified with } p(\nu)\right) \text {. }
$$

If $G \subseteq \mathbb{Q}$, then let $G \mid c=\{p \in G:|p| \subseteq c\}(=\{p \upharpoonright c: p \in G\}$ in case $c \in \mathbf{L})$.
Put $G \upharpoonright_{\neq \nu}=\left\{p \in G: \nu \notin|p|^{+}\right\}=G \upharpoonright\left(\mathcal{I}^{+} \backslash\{\nu\}\right)$.
Writing $p \upharpoonright c$, it is not assumed that $c \subseteq|p|^{+}$.
The proof of Theorem 1.1 makes use of a generic extension of the form $\mathbf{L}[G \upharpoonright c]$, where $G \subseteq \mathbb{Q}$ is a set $\mathbb{Q}$-generic over $\mathbf{L}$ and $c \subseteq \mathcal{I}^{+}, c \notin \mathbf{L}$.

Define formulas $\mathbb{『}_{\nu}(\nu \in \mathcal{I})$ as follows:

$$
\mathbb{『}_{\nu}(S):==_{\text {def }} S \subseteq \operatorname{Seq} \wedge \forall f \in \operatorname{Fun}(f \in \mathbb{U}(\nu) \Longleftrightarrow S \text { does not cover } f) .
$$

Lemma 6.2 (Lemma 22 in [17). Suppose that a set $G \subseteq \mathbb{Q}$ is $\mathbb{Q}$-generic over $\mathbf{L}$ and $\nu \in \mathcal{I}, c \in \mathbf{L}[G], \varnothing \neq c \subseteq \mathcal{I}^{+}$. Then, $\omega_{1}^{\mathbf{L}[G\lceil c]}=\omega_{2}^{\mathbf{L}}$ and
(i) $\mathbb{V}_{\nu}\left(S_{G}(\nu)\right)$ holds;
(ii) $S_{G}(\nu) \notin \mathbf{L}\left[G \upharpoonright_{\neq \nu}\right]$-generally, there are no sets $S \subseteq \mathbf{S e q}$ in $\mathbf{L}\left[G \upharpoonright_{\neq \nu}\right]$ satisfying $\llbracket_{\nu}(S)$;
(iii) if $-1 \in c$, then $\boldsymbol{b}_{G} \in \mathbf{L}[G \upharpoonright c]$, and if $\nu \in c$, then $S_{G}(\nu) \in \mathbf{L}[G \upharpoonright c]$.

The next key theorem is Theorem 4 in [17]. Note that if $\mathfrak{n}=2$, then the result is an easy corollary of the Shoenfield absoluteness theorem.

Theorem 6.3 (elementary equivalence theorem). Assume that in $\mathbf{L},-1 \in d \subseteq$ $\mathcal{I}^{+}$, sets $Z^{\prime}, Z \subseteq \mathcal{I} \backslash d$ satisfy $\operatorname{card}(\mathcal{I} \backslash Z) \leq \omega_{1}$ and $\operatorname{card}\left(\mathcal{I} \backslash Z^{\prime}\right) \leq \omega_{1}$, the symmetric difference $Z \Delta Z^{\prime}$ is at most countable and the complementary set $\mathcal{I} \backslash\left(d \cup Z \cup Z^{\prime}\right)$ is infinite.

Let $G \subseteq \mathbb{Q}$ be $\mathbb{Q}$-generic over $\mathbf{L}$, and $x_{0} \in \mathbf{L}[G \upharpoonright d]$ be any real.
Then, any closed $\Sigma_{m}^{1}$ formula $\varphi$, with real parameters in $\mathbf{L}\left[x_{0}\right]$, is simultaneously true in the models $\mathbf{L}\left[x_{0}, G \upharpoonright Z\right]$ and $\mathbf{L}\left[x_{0}, G \upharpoonright Z^{\prime}\right]$.

## 7 The model

Here, we introduce a submodel of the basic $\mathbb{Q}$-generic extension $\mathbf{L}[G]$ defined in Section 6 that will lead to the proof of Theorem 1.1 .

Recall that a number $n \geq 2$ is fixed by Definition 5.2,
Under the assumptions and notation of Definition 5.2, consider a set $G \subseteq \mathbb{Q}$, $\mathbb{Q}$-generic over $\mathbf{L}$. Then, $\boldsymbol{b}_{G}=\bigcup G(-1)$ is a $\mathbb{C}$-generic map from $\omega$ onto $\mathscr{P}(\omega) \cap \mathbf{L}$ by Lemma 6.1 (i). We define

$$
\begin{equation*}
w[G]=\left\{\omega k+2^{j}: k<\omega \wedge j \in \boldsymbol{b}_{G}(k)\right\} \cup\left\{\omega k+3^{j}: j, k<\omega\right\} \subseteq \omega^{2} \tag{3}
\end{equation*}
$$

and $w^{+}[G]=\{-1\} \cup w[G]$. We also define, for any $m<\omega$,

$$
w_{\geq m}[G]=\{\omega k+\ell \in w[G]: k \geq m\}, \quad w_{<m}[G]=\{\omega k+\ell \in w[G]: k<m\}
$$

and accordingly, $w_{\geq m}^{+}[G]=\{-1\} \cup w_{\geq m}[G]$ and $w_{<m}^{+}[G]=\{-1\} \cup w_{<m}[G]$.
With these definitions, each $k$ th slice

$$
\begin{equation*}
w_{k}[G]=\left\{\omega k+2^{j}: j \in \boldsymbol{b}_{G}(k)\right\} \cup\left\{\omega k+3^{j}: j<\omega\right\} \tag{4}
\end{equation*}
$$

of $w[G]$ is necessarily infinite and coinfinite, and it codes the target set $\boldsymbol{b}_{G}(k)$ since

$$
\begin{equation*}
\boldsymbol{b}_{G}(k)=\left\{j<\omega: \omega k+2^{j} \in w_{k}[G]\right\}=\left\{j<\omega: \omega k+2^{j} \in w^{+}[G]\right\} \tag{5}
\end{equation*}
$$

Note that definition (3) is monotone w.r.t. $\boldsymbol{b}_{G}$, i.e., if $\boldsymbol{b}_{G}(k) \subseteq \boldsymbol{b}_{G^{\prime}}(k)$ for all $k$, then $w[G] \subseteq w\left[G^{\prime}\right]$ and $w^{+}[G] \subseteq w^{+}\left[G^{\prime}\right]$. Anyway, $w[G] \subseteq \omega^{2}$ (the ordinal product) is a set in the model $\mathbf{L}\left[\boldsymbol{b}_{G}\right]=\mathbf{L}\left[w^{+}[G]\right]=\mathbf{L}[w[G]]=\mathbf{L}\left[w_{\geq m}[G]\right]$ for each $m$, whereas $w_{<m}[G] \in \mathbf{L}$ for all $m$. Finally, let $W=\left[\omega^{2}, \omega_{2}\right)=\left\{\zeta: \omega^{2} \leq \zeta<\omega_{2}\right\}$.

Recall that if $c \subseteq \mathcal{I}^{+}$, then $G \upharpoonright c=\left\{p \in G:|p|^{+} \subseteq c\right\}$.
To prove Theorem 1.1, we consider the model $\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup W\right)\right] \subseteq \mathbf{L}[G]$.
Theorem 7.1. If $G$ is a $\mathbb{Q}$-generic set over $\mathbf{L}$, then the class $\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup W\right)\right]$ suffices to prove Theorem 1.1. That is, Lightface Separation holds in $\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup\right.\right.$ $W)]$ both for $\Sigma_{m+1}^{1}$ sets of integers and for $\Pi_{n+1}^{1}$ sets of integers.

The proof will include several lemmas.
For the next lemma, we let $\Vdash_{\mathbb{Q}}$ be the $\mathbb{Q}$-forcing notion defined in $\mathbf{L}$. If $p \in \mathbb{Q}$ and $-1 \in|p|^{+}$, then let $p \upharpoonright_{-1}:=p \upharpoonright\{-1\}$. This can be identified with just $p(-1) \in \mathbb{C}$, of course, but formally $p \upharpoonright_{-1} \in \mathbb{Q}$. If $-1 \notin|p|^{+}$, then let $p \upharpoonright_{-1}:=\odot$ (the empty condition). Let $\underline{G}$ be the canonical $\mathbb{Q}$-name for the generic set $G \subseteq \mathbb{Q}$, $\check{W}$ be a name for the set $W=\left[\omega^{2}, \omega_{2}^{\mathbf{L}}\right) \in \mathbf{L}$, and $\check{\boldsymbol{b}}$ be a canonical $\mathbb{Q}$-name for $\boldsymbol{b}_{G}$.

Lemma 7.2 (reduction to the $\mathbb{C}$-component). Let $p \in \mathbb{Q}$ and let $\Phi(\check{\boldsymbol{b}})$ be a closed formula containing only $\check{\boldsymbol{b}}$ and names for sets in $\mathbf{L}$ as parameters. Assume that

$$
p \Vdash_{\mathbb{Q}} \text { " } \Phi \text { is true in } \mathbf{L}\left[\underline{G} \upharpoonright\left(w^{+}[\underline{G}] \cup \check{W}\right)\right]^{\prime \prime} \text {. }
$$

Then, $p \upharpoonright_{-1} \Vdash_{\mathbb{Q}}$ " $\Phi$ is true in $\mathbf{L}\left[\underline{G} \upharpoonright\left(w^{+}[\underline{G}] \cup \check{W}\right)\right]$ " as well.
Proof. By the product forcing theorem, if $G \subseteq \mathbb{Q}$ is $\mathbb{Q}$-generic over $\mathbf{L}$, then the model $\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup W\right)\right]$ is a $\mathbb{Q}^{\prime}$-generic extension of $\mathbf{L}\left[\boldsymbol{b}_{G}\right]$, where $\mathbb{Q}^{\prime}=$ $\prod_{\nu \in w^{+}[G] \cup W} Q[\cup(\nu)]$ is a forcing in $\mathbf{L}\left[\boldsymbol{b}_{G}\right]$. However, it follows from Corollary 3.2 that $\mathbb{Q}^{\prime}$ is a (finite-support) product of cone-homogeneous forcing notions. Therefore, $\mathbb{Q}^{\prime}$ itself is a cone homogeneous forcing, and we are finished (see e.g., Lemma 3 in [5] or Theorem IV.4.15 in [20]).

## 8 Two key lemmas

The following two lemmas present two key properties of models of the form $\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup\right.\right.$ $W)$ ] involved in the proof of Theorem [7.1. The first lemma shows that all constructible reals are $\Delta_{\mathrm{m}+1}^{1}$ in such a model.
Lemma 8.1. Let a set $G \subseteq \mathbb{Q}$ be $\mathbb{Q}$-generic over $\mathbf{L}$. Then, it holds in $\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup\right.\right.$ $W)]$ that $w[G]$ is $\Sigma_{\mathfrak{m}+1}^{1}$ and each set $x \in \mathbf{L}, x \subseteq \omega$ is $\Delta_{m+1}^{1}$.
Proof. Consider an arbitrary ordinal $\nu=\omega k+\ell ; k, \ell<\omega$. We claim that

$$
\begin{equation*}
\nu \in w[G] \Longleftrightarrow \exists S \mathbb{『}_{\nu}(S) \tag{6}
\end{equation*}
$$

holds in $\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup W\right)\right]$. Indeed, assume that $\nu \in w[G]$. Then, $S=S_{G}(\nu) \in$ $\mathbf{L}\left[G \upharpoonright w^{+}[G]\right]$, and we have $\mathbb{V}_{\nu}(S)$ in $\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup W\right)\right]$ by Lemma 6.2 (iii) (i), Conversely, assume that $\nu \notin w[G]$. Then, we have $w^{+}[G] \in \mathbf{L}\left[\boldsymbol{b}_{G}\right] \subseteq \mathbf{L}\left[G \upharpoonright w^{+}[G]\right] \subseteq$ $\mathbf{L}\left[G \upharpoonright_{\neq \nu}\right]$, but $\mathbf{L}\left[G \upharpoonright_{\neq \nu}\right]$ contains no $S$ with $\mathbb{T}_{\nu}(S)$ by Lemma 6.2 (ii),

Let $\mathfrak{k}:=\omega_{2}{ }^{\mathrm{L}}$ in the remainder of the proof of the lemma. Then it follows that ${ }_{\kappa}=\omega_{1}^{\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup W\right)\right]}=\omega_{1}^{\mathbf{L}[G]}$, by Lemma 6.2,

Note that the right-hand side of (6) defines a $\Sigma_{m}^{\mathrm{Hx}}\left(\left\{\omega_{1}^{\mathbf{L}}, \mathbf{S e q}\right\}\right)$ relation in the model $\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup W\right)\right]$ by Lemma 5.3. (Indeed, we have $\left(\mathrm{H}_{\kappa}\right)^{\mathbf{L}}=\left(\mathrm{H} \omega_{2}\right)^{\mathbf{L}}=$ $\mathbf{L}_{\omega_{2} \mathbf{L}}=\mathbf{L}_{\kappa<}$ in $\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup W\right)\right]$, therefore $\left(\mathrm{H}_{\kappa}\right)^{\mathbf{L}}$ is $\Sigma_{1}^{\mathrm{H}}$ in $\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup\right.\right.$ $W)]$.) On the other hand, the sets $\left\{\omega_{1}^{\mathrm{L}}\right\}$ and $\{$ Seq $\}$ remain $\Delta_{2}^{\mathrm{H} \omega_{2}}$ singletons in $\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup W\right)\right]$; they can be eliminated since $\llbracket \geq 2$. This yields $w[G] \in \Sigma_{\mathrm{m}}^{\mathrm{H} \mathrm{\kappa}}=$ $\Sigma_{\mathfrak{m}}^{\mathrm{H} \omega_{1}}$ in $\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup W\right)\right]$. It follows that $w[G] \in \Sigma_{\mathfrak{m}+1}^{1}$ in $\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup W\right)\right]$ by Lemma 25.25 in [10], as required.

Now, let $x \in \mathbf{L}, x \subseteq \omega$. By genericity, there exists $k<\omega$ such that $\boldsymbol{b}_{G}(k)=x$. Then, $x=\left\{j: \omega k+2^{j} \in w[G]\right\}$ by (3); therefore, $x$ is $\Sigma_{m+1}^{1}$ as well. However, $\omega \backslash x \in \Sigma_{\mathrm{m}+1}^{1}$ by the same argument. Thus, $x$ is $\Delta_{\mathrm{m}+1}^{1}$ in $\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup W\right)\right]$, as required.

The proof of the next lemma involves Theorem 6.3 above as a key reference. The lemma holds for $n=2$ by Shoenfield.

Lemma 8.2. Suppose that $G \subseteq \mathbb{Q}$ is $\mathbb{Q}$-generic over $\mathbf{L}, m<\omega, c \subseteq w_{<m}[G], c \in$ $\mathbf{L}$. Then, any closed $\Sigma_{\mathrm{m}}^{1}$ formula $\Phi$, with reals in $\mathbf{L}\left[G \upharpoonright\left(c \cup w_{\geq m}^{+}[G] \cup W\right)\right]$ as parameters, is simultaneously true in $\mathbf{L}\left[G \upharpoonright\left(c \cup w_{\geq m}^{+}[G] \cup W\right)\right]$ and in $\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup W\right)\right]$.

It follows that if $c^{\prime} \subseteq c \subseteq w_{<m}[G]$ in $\mathbf{L}$, then any closed $\Sigma_{m+1}^{1}$ formula $\Psi$, with parameters in $\mathbf{L}\left[G \upharpoonright\left(c^{\prime} \cup w_{\geq m}^{+}[G] \cup W\right)\right]$, true in $\mathbf{L}\left[G \upharpoonright\left(c^{\prime} \cup w_{\geq m}^{+}[G] \cup W\right)\right]$, is true in the model $\mathbf{L}\left[G \upharpoonright\left(c \cup w_{\geq m}^{+}[G] \cup W\right)\right]$ as well.
Proof. There is an ordinal $\xi<\omega_{2}$ such that all parameters in $\varphi$ belong to $\mathbf{L}[G \upharpoonright Y]$, where $Y=c \cup w_{\geq m}^{+}[G] \cup X$ and $X=\left[\omega^{2}, \xi\right)=\left\{\gamma: \omega^{2} \leq \gamma<\xi\right\}$. The set $Y$ belongs to $\mathbf{L}\left[\boldsymbol{b}_{G}\right]$; in fact, $\mathbf{L}[Y]=\mathbf{L}\left[\boldsymbol{b}_{G}\right]$. Therefore, $G \upharpoonright Y$ is equi-constructible with the pair $\left\langle\boldsymbol{b}_{G},\left\{S_{G}(\nu)\right\}_{\nu \in Y}\right\rangle$. Here, $\boldsymbol{b}_{G}$ is a map from $\omega$ onto $\mathscr{P}(\omega) \cap \mathbf{L}$. It follows that there is a real $x_{0}$ with $\mathbf{L}[G \upharpoonright Y]=\mathbf{L}\left[x_{0}\right]$. Then, all parameters of $\varphi$ belong to $\mathbf{L}\left[x_{0}\right]$.

To prepare an application of Theorem 6.3 of Section 6, we put

$$
\begin{aligned}
Z^{\prime} & =\left[\xi, \omega_{2}\right), \\
Z & =e \cup Z^{\prime}, \quad \text { where } \quad e=w_{<m}[G] \backslash c, \\
d & =\{-1\} \cup\{\omega k+j: k \geq m \wedge j<\omega\} \cup X .
\end{aligned}
$$

It is easy to check that all requirements of Theorem 6.3 for these sets are fulfilled. Moreover, as $w_{\geq m}^{+}[G] \subseteq\{-1\} \cup\{\omega k+j: k \geq m \wedge j<\omega\}$, we have $Y=c \cup$ $w_{\geq m}^{+}[G] \cup X \subseteq d$; hence, $x_{0} \in \mathbf{L}[G \upharpoonright d]$. Therefore, we conclude by Theorem 6.3 that the formula $\varphi$ is simultaneously true in $\mathbf{L}\left[x_{0}, G \upharpoonright Z\right]$ and in $\mathbf{L}\left[x_{0}, G \upharpoonright Z^{\prime}\right]$. However,

$$
\mathbf{L}\left[x_{0}, G \upharpoonright Z^{\prime}\right]=\mathbf{L}\left[G \upharpoonright\left(Y \cup Z^{\prime}\right)\right]=\mathbf{L}\left[G \upharpoonright\left(c \cup w_{\geq m}^{+}[G] \cup W\right)\right]
$$

by construction, while $\mathbf{L}\left[x_{0}, G \upharpoonright Z\right]=\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup W\right)\right]$, and we are done.

## $9 \quad$ Finalization: $\Sigma_{m+1}^{1}$ case

Here, we finalize the proof of Theorems 7.1 and 1.1 w.r.t. $\Sigma_{m+1}^{1}$ sets of integers. We generally follow the line of arguments sketched by Harrington ([Addendum A3] 8]) for the $\Sigma_{3}^{1}$ case, with suitable changes mutatis mutandis. We will fill in all details omitted in [8].

Recall that a number $n \geq 2$ is fixed by Definition 5.2. We assume that
$(*)$ a set $G \subseteq \mathbb{Q}$ is $\mathbb{Q}$-generic over $\mathbf{L}$, sets $x, y \subseteq \omega$ belong to $\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup W\right)\right]$, and it holds in $\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup W\right)\right]$ that $x, y$ are disjoint $\Sigma_{\mathfrak{m}+1}^{1}$ sets.

The goal is to prove that $x, y$ can be separated by a set $Z \in \mathbf{L}$ and then argue that $Z$ is $\Delta_{n+1}^{1}$ by Lemma 8.1. Recall that $W=\left[\omega^{2}, \omega_{2}^{\mathbf{L}}\right)=\left\{\xi: \omega^{2} \leq \xi<\omega_{2}^{\mathbf{L}}\right\}$. Suppose that
$(\dagger) \varphi(\cdot)$ and $\psi(\cdot)$ are parameter-free $\Sigma_{\mathrm{m}+1}^{1}$ formulas that provide $\Sigma_{\mathrm{m}+1}^{1}$ definitions for the sets, respectively, $x, y$ of (*)- that is,

$$
x=\{\ell<\omega: \varphi(\ell)\} \quad \text { and } \quad y=\{\ell<\omega: \psi(\ell)\}
$$

in $\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup W\right)\right]$. The assumed implication $\forall \ell(\varphi(\ell) \Longrightarrow \neg \psi(\ell))$ (as $x \cap y=\varnothing)$ is forced to be true in $\mathbf{L}\left[\underline{G} \upharpoonright\left(w^{+}[\underline{G}] \cup \check{W}\right)\right]$ by a condition $p_{0} \in G$.

Here, $\underline{G}$ is the canonical $\mathbb{Q}$-name for the generic set $G \subseteq \mathbb{Q}$ while $\check{W}$ is a name for the set $W=\left[\omega^{2}, \omega_{2}^{\mathbf{L}}\right) \in \mathbf{L}$.

We observe that $\forall \ell(\varphi(\ell) \Longrightarrow \neg \psi(\ell))$ is a parameter-free sentence. Therefore, it can w.l.o.g. be assumed that $\left|p_{0}\right|^{+}=\{-1\}$, by Lemma 7.2. In this case, the condition $p_{0} \in \mathbb{Q}$ can be identified with its only nontrivial component $s_{0}=$ $p_{0}(-1) \in \mathbb{C}$.

Lemma 9.1 (interpolation lemma). Under the assumptions of ( $\dagger$ ), if $\ell, \ell^{\prime}<\omega$, conditions $p, p^{\prime} \in \mathbb{Q}$ satisfy $p \leq p_{0}$ and $p^{\prime} \leq p_{0}$, and we have
$p \vdash_{\mathbb{Q}}$ " $\mathbf{L}\left[\underline{G} \upharpoonright\left(w^{+}[\underline{G}] \cup \check{W}\right)\right] \models \varphi(\ell) " \quad$ and $\quad p^{\prime} \Vdash_{\mathbb{Q}} " \mathbf{L}\left[\underline{G} \upharpoonright\left(w^{+}[\underline{G}] \cup \check{W}\right)\right] \models \psi\left(\ell^{\prime}\right)$ ".
Then, $\ell \neq \ell^{\prime}$.
Proof (sketched in [8, Addendum A3] for $n=2$ ). First of all, by Lemma [7.2, we can w.l.o.g. assume that $|p|^{+}=\left|p^{\prime}\right|^{+}=\{-1\}$; so, the components $s=p(-1)$ and $s^{\prime}=p^{\prime}(-1)$ satisfy $s_{0} \subseteq s$ and $s_{0} \subseteq s^{\prime}$ in $\mathbb{C}$.

We w.l.o.g. assume that the tuples $s, s^{\prime}$ have the same length $\operatorname{lh} s=\operatorname{lh} s^{\prime}=m$. (Otherwise, extend the shorted one by a sufficient number of new terms equal to $\varnothing$.) Define another condition $t \in \mathbb{C}$ such that $\operatorname{dom} t=m$ and $t(j)=s(j) \cup s^{\prime}(j)$ for all $j<m$. Accordingly, define $q \in \mathbb{Q}$ so that $|q|^{+}=\{-1\}$ and $q(-1)=t$. Despite that $q$ may well be incomparable with $p, p^{\prime}$ in $\mathbb{Q}$, we claim that

$$
\begin{equation*}
q \vdash_{\mathbb{Q}} " \mathbf{L}\left[\underline{G} \upharpoonright\left(w^{+}[\underline{G}] \cup \check{W}\right)\right] \models \varphi(\ell) \wedge \psi\left(\ell^{\prime}\right) " \tag{7}
\end{equation*}
$$

To prove the $\varphi$-part of (7), let $H \subseteq \mathbb{Q}$ be a set $\mathbb{Q}$-generic over $\mathbf{L}$, and $q \in H$. Then, $t \subset \boldsymbol{b}_{H}$. We have to prove that $\varphi(\ell)$ holds in $\mathbf{L}\left[H \upharpoonright\left(w^{+}[H] \cup W\right)\right]$.

Define another generic set $K \subseteq \mathbb{Q}$, slightly different from $H$, so that
(A) $K(\nu)=H(\nu)$ for all $\nu \in \mathcal{I}=\omega_{2}^{\mathbf{L}}$;
(B) $s \subset \boldsymbol{b}_{K}$; and
(C) if $m \leq j<\omega$, then $\boldsymbol{b}_{K}(j)=\boldsymbol{b}_{H}(j)$.

In other words, the only difference between $K$ and $H$ is that $\boldsymbol{b}_{K} \upharpoonright m=s$ but $\boldsymbol{b}_{H} \upharpoonright m=t$.

It follows that $p \in K$; hence, $\varphi(\ell)$ holds in $\mathbf{L}\left[K \upharpoonright\left(w^{+}[K] \cup W\right)\right]$ by the assumptions of the lemma. Now, we note that by definition,

$$
w^{+}[K] \cup W=w_{<m}[K] \cup w_{\geq m}^{+}[K] \cup W, \quad w^{+}[H] \cup W=w_{<m}[H] \cup w_{\geq m}^{+}[H] \cup W,
$$

Here, the sets $c_{H}=w_{<m}[H]$ and $c_{K}=w_{<m}[K]$ satisfy $c_{K} \subseteq c_{H}$ (since $\boldsymbol{b}_{K}(j)=$ $s(j) \subseteq t(j)=\boldsymbol{b}_{H}(j)$ for all $\left.j<m\right)$. In addition, $w_{\geq m}^{+}[H]=w_{\geq m}^{+}[K]$ (since $\boldsymbol{b}_{K}(j) \boldsymbol{b}_{H}(j)$ for all $\left.j \geq m\right)$. To conclude,

$$
\begin{equation*}
w^{+}[K] \cup W=c_{K} \cup w_{\geq m}^{+}[H] \cup W, \quad w^{+}[H] \cup W=c_{H} \cup w_{\geq m}^{+}[H] \cup W, \tag{8}
\end{equation*}
$$

and $c_{K} \subseteq c_{H}=w_{<m}[H]$. On the other hand, it follows from (A) that $K \upharpoonright c=H\lceil c$ for any $c \subseteq \mathcal{I}$, whereas $\boldsymbol{b}_{K}$ and $\boldsymbol{b}_{H}$ are recursively reducible to each other by (B),(C). Therefore,

$$
\mathbf{L}\left[K \upharpoonright\left(w^{+}[K] \cup W\right)\right]=\mathbf{L}\left[H \upharpoonright\left(w^{+}[K] \cup W\right)\right]=\mathbf{L}\left[H \upharpoonright\left(c_{K} \cup w_{\geq m}^{+}[H] \cup W\right)\right]
$$

by (8). However, $\varphi(\ell)$ holds in this model by the above. It follows by Lemma 8.2 that $\varphi(\ell)$ holds in $\mathbf{L}\left[H \upharpoonright\left(w^{+}[H] \cup W\right)\right]=\mathbf{L}\left[c_{H} \cup w_{\geq m}^{+}[H] \cup W\right]$ as well. (Harrington circumvents Lemma 8.2 in [8] by a reference to the Shoenfield absoluteness theorem.) We are finished.

After (7) has been established, we recall that $q \leq p_{0}$ in $\mathbb{Q}$ by construction. It follows that $\ell \neq \ell^{\prime}$ by the choice of $p_{0}$ (see ( $\dagger$ ) above).

Proof (Theorems 7.1] and 1.1] $\Sigma_{\mathrm{m}+1}^{1}$ case). We work under the assumptions of (*) and $(\dagger)$ above. Consider the following sets in $\mathbf{L}$ :

$$
\begin{aligned}
& Z_{x}=\left\{\ell<\omega: \exists p \in \mathbb{Q}\left(p \leq p_{0} \wedge p \Vdash_{\mathbb{Q}} " \mathbf{L}\left[\underline{G} \upharpoonright\left(w^{+}[\underline{G}] \cup \check{W}\right)\right] \models \varphi(\ell) "\right)\right\} ; \\
& Z_{y}=\left\{\ell^{\prime}<\omega: \exists p^{\prime} \in \mathbb{Q}\left(p^{\prime} \leq p_{0} \wedge p^{\prime} \vdash_{\mathbb{Q}} " \mathbf{L}\left[\underline{G} \upharpoonright\left(w^{+}[\underline{G}] \cup \check{W}\right)\right] \models \psi\left(\ell^{\prime}\right) "\right)\right\} .
\end{aligned}
$$

Note that $Z_{x} \cap Z_{y}=\varnothing$ by Lemma 9.1. On the other hand, it is clear that $x \subseteq Z_{x}$ and $y \subseteq Z_{y}$ by ( $\dagger$. Thus, either of the two sets $Z_{x}, Z_{y} \in \mathbf{L}$ separates $x$ from $y$. It remains to apply Lemma 8.1,

## 10 Finalization: $\Pi_{\mathrm{m}+1}^{1}$ case

This will be a mild variation of the argument presented in the previous section.
Proof (Theorems 7.1] and 1.1 $\Pi_{\mathrm{m}+1}^{1}$ case, sketch). Emulating (*) and ( $\dagger$ ) above, we assume that a set $G \subseteq \mathbb{Q}$ is $\mathbb{Q}$-generic over $\mathbf{L}$, and $x, y \subseteq \omega$ are disjoint $\Pi_{\mathfrak{n}+1}^{1}$ sets in $\mathbf{L}\left[G \upharpoonright\left(w^{+}[G] \cup W\right)\right]$, defined by parameter-free $\Pi_{\mathrm{m}+1}^{1}$ formulas, respectively, $\varphi(\cdot)$ and $\psi(\cdot)$. The implication $\forall \ell(\varphi(\ell) \Longrightarrow \neg \psi(\ell))$ is forced to hold in $\mathbf{L}\left[\underline{G} \upharpoonright\left(w^{+}[\underline{G}] \cup\right.\right.$ $\breve{W})$ ] by a condition $p_{0} \in G$ satisfying $\left|p_{0}\right|^{+}=\{-1\}$. The proof of Lemma 9.1 goes on for $\Pi_{\mathrm{m}+1}^{1}$ formulas $\varphi, \psi$ the same way, with the only difference that we define $t(j)=s(j) \cap s^{\prime}(j)$ for $j<m$. Yet, this is compatible with the application of Lemma 8.2 because now, $\varphi, \psi$ are $\Pi_{\mathrm{m}+1}^{1}$ formulas.

## 11 Conclusions and discussion

In this study, the method of almost-disjoint forcing was employed to the problem of obtaining a model of ZFC in which the Separation principle holds for lightface classes $\Pi_{n+1}^{1}$ and $\Sigma_{n+1}^{1}$, for a given $n \geq 2$, for sets of integers. The problem of obtaining such models has been generally known since the early years of modern set theory, see, e.g., problems 3029 and 3030 in a survey [24] by Mathias. Harrington [8, Addendum A3] claimed the existence of such models; yet, a detailed proof has never appeared.

From our study, it is concluded that the technique developed in our earlier paper [17] solves the general case of the problem (an arbitrary $n \geq 2$ ) by providing a generic extension of $\mathbf{L}$ in which the Lightface Separation principle holds for classes $\Pi_{n+1}^{1}$ and $\Sigma_{n+1}^{1}$, for a given $n \geq 2$, for sets of integers, for a chosen value $n \geq 2$.

From this result, we immediately come to the following problem:
Problem 11.1. Define a generic extension of $\mathbf{L}$ in which the Lightface Separation principle holds for classes $\Pi_{n+1}^{1}$ and $\Sigma_{n+1}^{1}$, for all $n \geq 2$, for sets of integers.

The intended solution is expected to be obtained on the basis of a suitable product of the forcing notions $\mathbb{Q}_{m}, m \geq 2$, defined in Section 6.

And we recall the following major problem.
Problem 11.2. Given $n \geq 2$, define a generic extension of $\mathbf{L}$ in which the Separation principle holds for the classes $\Sigma_{n+1}^{1}$ and $\boldsymbol{\Sigma}_{n+1}^{1}$ for sets of reals.

The case of sets of reals in the Separation problem is more general, and obviously much more difficult, than the case sets of integers.

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    ${ }^{\dagger}$ IITP RAS, kanovei@iitp.ru .
    ${ }^{\ddagger}$ IITP RAS, lyubetsk@iitp.ru.

