COMPLEXITY OF DEEP COMPUTATIONS
VIA TOPOLOGY OF FUNCTION SPACES

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ABSTRACT. This paper revisits and extends a bridge between functional analysis and model theory, emphasizing its relevance to the theoretical foundations of machine learning. We show that the compactness behavior of families of Baire class 1 functions mirrors the learnability conditions in the sense of *Probably Approximately Correct* (PAC) learning, and that the failure of compactness corresponds to the presence of infinite *Vapnik-Chervonenkis* (VC) dimension. From this perspective, Rosenthal compacta emerge as the natural topological counterpart of PAC-learnable concept classes, while NIP vs. IP structures capture the precise boundary between analytical regularity and combinatorial intractability. These parallels suggest a unified framework linking compactness, definability, and learnability, exemplifying how the topology of function spaces encodes the algorithmic and epistemic limits of prediction.

1. INTRODUCTION

In this paper we study limit behavior of real-valued computations as the value of certain parameters of the computation model tend towards infinity, or towards zero, or towards some other fixed value, e.g., the depth of a neural network tending to infinity, or the time interval between layers of the network tending toward zero. Recently, particular cases of this situation have attracted considerable attention in deep learning research (e.g., Neural Ordinary Differential Equations [CRBD], Physics-Informed Neural Networks [RPK19], deep equilibrium models [BKK], etc). In this paper, we combine ideas of topology and model theory to study these limit phenomena from a unified viewpoint.

Informed by model theory, to each computation in a given computation model, we associate a continuous real-valued function, called the *type* of the computation, that describes the logical properties of this computation with respect to the rest of the model. This allows us to view computations in any given computational model as elements of a space of real-valued functions, which is called the *space of types* of the model. The idea of embedding models of theories into their type spaces is central in model theory. The embedding of computations into spaces of types allows us to utilize the vast theory of topology of function spaces, known as C_p-theory, to obtain results about complexity of topological limits of computations. As we shall indicate next, recent classification results for spaces of functions provide an elegant and powerful machinery to classify computations according to their levels of "tameness" or "wildness", with the former corresponding roughly to polynomial approximability and the latter to exponential approximability. The viewpoint of spaces of types, which we have borrowed from model theory, thus becomes a "Rosetta stone" that allows us to interconnect various classification programs: In

topology, the classification of Rosenthal compacta pioneered by Todorčević [Tod99]; in logic, the classification of theories developed by Shelah [She90]; and in statistical learning, the notion PAC learning and VC dimension pioneered by Vapkins and Chervonenkis [VC74, VC71].

In a previous paper [ADIW24], we introduced the concept of limits of computations, which we called *ultracomputations* (given they arise as ultrafilter limits of standard computations) and *deep computations* (following usage in machine learning [BKK]). There is a technical difference between both designations, but in this paper, to simplify the nomenclature, we will ignore the difference and use only the term "deep computation".

In [ADIW24], we proved a new "tame vs wild" (i.e., polynomial vs exponential) dichotomy for complexity of deep computations by invoking a classical result of Grothendieck from late 50s [Gro52]. Under our model-theoretic Rosetta stone, polynomial approximability in the sense of computation becomes identified with the notion of continuous extendability in the sense of topology, and with the notions of *stability* and *type definability* in the sense of model theory.

In this paper, we follow a more general approach, i.e., we view deep computations as pointwise limits of continuous functions. In topology, real-valued functions that arise as the pointwise limit of a sequence of continuous are called *functions of the first Baire class*, or *Baire class 1* functions, or *Baire-1* for short; Baire class 1 form a step above simple continuity in the hierarchy of functions studied in real analysis (Baire class 0 functions being continuous functions). Intuitively, Baire-1 functions represent functions with "controlled" discontinuities, so they are crucial in topology and set theory.

We prove a new "tame vs wild" Ramsey-theoretic dichotomy for complexity of general deep computations by invoking a famous paper by Bourgain, Fremlin and Talagrand from the late 70s [BFT78], and a new trichotomy for the class of "tame" deep computations by invoking an equally celebrated result of Todorčević, from the late 90s, for functions of the first Baire class [Tod99].

Todorčević's trichotomy regards *Rosenthal compacta*; these are special classes of topological spaces, defined as compact spaces that can be embedded (homeomorphically identified as a subset) within the space of Baire class 1 functions on some Polish (separable, complete metric) space, under the pointwise convergence topology. Rosenthal compacta exhibit "topological tameness," meaning they behave in relatively controlled ways, and since the late 70's, they have played a crucial role for understanding complexity of structures of functional analysis, especially, Banach spaces. Todorčević's trichotomy has been utilized to settle longstanding problems in topological dynamics and topological entriopy [GM22].

Through our Rosetta stone, Rosenthal compacta in topology correspond to the important concept of "No Independence Property" (known as "NIP") in model theory, identified by Shelah [She71, She90], and to the concept of Probably Approximately Correct learning (known as "PAC learnability") in statistical learning theory identified by Valiant [Val84].

Going beyond Todorčević's trichotomy, we invoke a more recent heptachotomy for Rosenthal compacta obtained by Argyros, Dodos and Kanellopoulos [ADK08]. Argyros, Dodos and Kanellopoulos identified the fundamental "prototypes" of separable Rosenthal compacta, and proved that any non-metrizable separable Rosenthal compactum must contain a "canonical" embedding of one of these prototypes. They

showed that if a separable Rosenthal compactum is not hereditarily separable, it must contain an uncountable discrete subspace of the size of the continuum.

We believe that the results presented in this paper show practitioners of computation, or topology, or descriptive set theory, or model theory, how classification invariants used in their field translate into classification invariants of other fields. However, in the interest of accessibility, we do not assume previous familiarity with high-level topology or model theory, or computing. The only technical prerequisite of the paper is undergraduate-level topology. The necessary topological background beyond undergraduate topology is covered in section 2.

Throughout the paper, we focus on classical computation; however, by refining the model-theoretic tools, the results presented here can be extended to quantum computation and open quantum systems. This extension will be addressed in a forthcoming paper.

2. General topological preliminaries

In this section we give preliminaries from general topology and function space theory. We include some of the proofs for completeness, but the reader familiar with these topics may skip them.

Recall that a subset of a topological space is F_σ if it is a countable union of closed sets, and G_δ if it is a countable intersection of closed sets. Note that in a metrizable space, every open set is F_σ; equivalently, every closed set is G_δ.

A *Polish space* is a separable and completely metrizable topological space. The most important examples are the reals $\mathbb{R}$, the Cantor space $2^{\mathbb{N}}$ (the set of all infinite binary sequences, endowed with the product topology), and the Baire space $\mathbb{N}^{\mathbb{N}}$ (the set of all infinite sequences of naturals, also with the product topology). Countable products of Polish spaces are Polish; this includes spaces like $\mathbb{R}^{\mathbb{N}}$, the space of sequences of real numbers.

In this paper, we shall discuss subspaces, and so there is a pertinent subtlety of the definitions worth mentioning: *completely metrizable space* is not the same as *complete metric space*; for an illustrative example, the interval $(0, 1)$ with the metric inherited from the reals not complete, but it is Polish since that is homeomorphic to the real line. Being Polish is a topological property.

The folllowing result is a cornerstone of descriptive set theory, closely tied to the work of Wacław Sierpiński and Kazimierz Kuratowski, with proofs often attributed to or built upon their foundations and formalized later, notably involving Stefan Mazurkiewicz's work on complete metric spaces.

Fact 2.1. *A subset A of a Polish space X is itself Polish in the subspace topology if and only if it is a G_δ set. n particular, closed subsets and open subsets of Polish spaces are also Polish spaces.*

Given two topological spaces X and Y we denote by $C_p(X, Y)$ the set of all continuous functions $f : X \to Y$ endowed with the topology of pointwise convergence. When $Y = \mathbb{R}$, we denote this collection simply as $C_p(X)$. A natural question is, how do topological properties of X translate to $C_p(X)$ and vice versa? These questions, and in general the study of these spaces, are the concern of C_p-theory, an active field of research in general topology which was pioneered by A. V. Arhangel'skiĭ and his students in the 1970's and 1980's. This field has found many applications in model theory and functional analysis. Recent surveys on the topics include [HT23] and [Tka11].

A *Baire class 1* function between topological spaces is a function that can be expressed as the pointwise limit of a sequence of continuous functions. If X nd Y are topological spaces, the Baire class 1 functions $f : X \to Y$ endowed with the topology of pointwise convergence is denoted $B_1(X, Y)$. As above, in the special case $Y = \mathbb{R}$ we denote $B_1(X, Y)$. as $B_1(X)$. Clearly, $C_p(X, Y) \subseteq B_1(X, Y)$. The Baire hierarchy of functions was introduced by French mathematician René-Louis Baire in his 1899 doctoral thesis, *Sur les fonctions de variables réelles*. His work moved away from the 19th-century preoccupation with "pathological" functions toward a constructive classification based on pointwise limits.

A topological space X is *perfectly normal* if it is normal and every closed subset of X is a G_δ (equivalently, every open subset of X is a G_δ). Note that every metrizable space is perfectly normal.

The following fact was established by Baire in thesis. A proof can be found in Section 10 of [Tod97].

Fact 2.2 (Baire)**.** *If X is perfectly normal, then the following conditions are equivalent for a function $f : X \to \mathbb{R}$:*

- f *is a Baire class 1 function, that is,* $f \in B_1(X)$.
- $f^{-1}[U]$ *is an F_σ subset of X whenever $U \subseteq Y$ is open.*
- f *is a pointwise limit of continuous functions.*
- *For every closed $F \subseteq X$, the restriction $f|_F$ has a point of continuity.*

Moreover, if X is Polish and $f \notin B_1(X)$, then there exists countable $D_0, D_1 \subseteq X$ and reals $a < b$ such that

$$D_0 \subseteq f^{-1}(-\infty, a], \quad D_1 \subseteq f^{-1}[b, \infty), \quad \overline{D_0} = \overline{D_1}.$$

A subset L of a topological space X is *relatively compact* in X if the closure of L in X is compact. Relatively compact subsets of $B_1(X)$ (for X Polish space) have been objects of interest for researchers in Analysis and Topological Dynamics. We begin with the following well-known result. Recall that a set $A \subseteq \mathbb{R}^X$ of real-valued functions is *pointwise bounded* if for every $x \in X$ there is $M_x > 0$ such that $|f(x)| < M_x$ for all $f \in A$. We include a proof for the reader's convenience:

Lemma 2.3. *Let X be a Polish space and $A \subseteq B_1(X)$ be pointwise bounded. The following are equivalent:*

(i) A is relatively compact in $B_1(X)$.

(ii) A is relatively countably compact in $B_1(X)$, i.e., every countable subset of A has an accumulation point in $B_1(X)$.

(iii) $\overline{A} \subseteq B_1(X)$, where $\overline{A}$ denotes the closure in $\mathbb{R}^X$.

Proof. By definition, being pointwise bounded means that there is, for each $x \in X$, $M_x > 0$ such that, for every $f \in A$, $|f(x)| \leq M_x$.

(i)$\Rightarrow$(ii) holds in general.

(ii)$\Rightarrow$(iii) Assume that A is relatively countably compact in $B_1(X)$ and that $f \in \overline{A} \setminus B_1(X)$. By Fact 2.2, there are countable $D_0, D_1 \subseteq X$ with $\overline{D_0} = \overline{D_1}$, and $a < b$ such that $D_0 \subseteq f^{-1}(-\infty, a]$ and $D_1 \subseteq f^{-1}[b, \infty)$. We claim that there is a sequence $\{f_n\}_{n \in \mathbb{N}} \subseteq A$ such that for all $x \in D_0 \cup D_1$, $\lim_{n \to \infty} f_n(x) = f(x)$. Indeed, use the countability to enumerate $D_0 \cup D_1$ as $\{x_n\}_{n \in \mathbb{N}}$. Then find, for each positive n, $f_n \in A$ with $|f_n(x_i) - f(x_i)| < \frac{1}{n}$ for all $i \leq n$. The claim follows.

By relative countable compactness of A, there is an accumulation point $g \in B_1(X)$ of $\{f_n\}_{n \in \mathbb{N}}$. It is straightforward to show that since f and g agree on $D_0 \cup D_1$,

172 g does not have a point of continuity on the closed set $\overline{D_0} = \overline{D_1}$, which contradicts
173 Fact 2.2.

174 (iii)$\Rightarrow$(i) Suppose that $\overline{A} \subseteq B_1(X)$. Then $\overline{A} \cap B_1(X) = \overline{A}$ is a closed subset of
175 $\prod_{x \in X}[-M_x, M_x]$; Tychonoff's theorem states that the product of compact spaces
176 is always compact, and since closed subsets of compact spaces are compact, $\overline{A}$ must
177 be compact, as desired. $\qquad\square$

178 2.1. **From Rosenthal's dichotomy to NIP.** The fundamental idea that con-
179 nects the rich theory here presented to real-valued computations is the concept
180 of an *approximation*. In the reals, points of closure from some subset can always
181 be approximated by points inside the set, via a convergent sequence. For more
182 complicated spaces, such as $C_p(X)$, this fails in a remarkably intriguing way. Let
183 us show an example that is actually the protagonist of a celebrated result. Con-
184 sider the Cantor space $X = 2^{\mathbb{N}}$ and let $p_n(x) = x(n)$ define a continuous mapping
185 $X \to \{0, 1\}$. Then one can show (see Chapter 1.1 of [Tod97] for details) that, per-
186 haps surprisingly, the only continuous functions in the closure of $\{p_n\}_{n \in \mathbb{N}}$ are the
187 functions p_n themselves; moreover, none of the subsequences of $\{p_n\}_{n \in \mathbb{N}}$ converge.
188 In some sense, this example is the worst possible scenario for convergence. The
189 topological space obtained from this closure is well-known. Topologists refer to it
190 as the Stone-Čech compactification of the discrete space of natural numbers, or $\beta\mathbb{N}$
191 for short, and it is an important object of study in general topology.

192 **Theorem 2.4** (Rosenthal's Dichotomy)**.** *If X is Polish and $\{f_n\} \subseteq C_p(X)$ is point-*
193 *wise bounded, then either $\{f_n\}_{n \in \mathbb{N}}$ contains a convergent subsequence or a subse-*
194 *quence whose closure (in $\mathbb{R}^X$) is homeomorphic to $\beta\mathbb{N}$.*

195 In other words, a pointwise bounded set of continuous functions will either con-
196 tain a subsequence that converges or a subsequence whose closure is essentially
197 the same as the example mentioned in the previous paragraphs (the worst possible
198 scenario). Note that in the preceding example, the functions are trivially pointwise
199 bounded in $\mathbb{R}^X$ as the functions can only take values 0 and 1.

200 If we intend to generalize our results from $C_p(X)$ to the bigger space $B_1(X)$, we
201 find a similar dichotomy. Either every point of closure of the set of functions will
202 be a Baire class 1 function, or there is a sequence inside the set that behaves in the
203 worst possible way (which in this context, is the IP!). The theorem is usually not
204 phrased as a dichotomy but rather as an equivalence (with the NIP instead):

205 **Theorem 2.5** (Bourgain-Fremlin-Talagrand, Theorem 4G in [BFT78])**.** *Let X be*
206 *a Polish space and $A \subseteq C_p(X)$ be pointwise bounded. The following are equivalent:*

207 *(i) A is relatively compact in $B_1(X)$, i.e., $\overline{A} \subseteq B_1(X)$.*

(ii) For every $\{f_n\}_{n \in \mathbb{N}} \subseteq A$ and for every $a < b$ there is $I \subseteq \mathbb{N}$ such that

$$\bigcap_{n \in I} f_n^{-1}(-\infty, a] \cap \bigcap_{n \notin I} f_n^{-1}[b, \infty) = \emptyset.$$

208 Our goal now is to characterize relatively compact subsets of $B_1(X, Y)$ when
209 $Y = \mathbb{R}^{\mathcal{P}}$ with $\mathcal{P}$ countable. Given $P \in \mathcal{P}$ we denote the *projection map* onto the
210 P-coordinate by $\pi_P : \mathbb{R}^{\mathcal{P}} \to \mathbb{R}$. From a high-level topological interpretation, the
211 subsequent lemma states that, in this context, the spaces $\mathbb{R}$ and $\mathbb{R}^{\mathcal{P}}$ are really not
212 that different, and that if we understand the Baire class 1 functions of one space,
213 then we also understand the functions of both. In fact, $\mathbb{R}$ and any other Polish
214 space is embeddable as a closed subspace of $\mathbb{R}^{\mathcal{P}}$.

Lemma 2.6. *Let X be a Polish space and $\mathcal{P}$ be a countable set. Then, $f \in B_1(X, \mathbb{R}^{\mathcal{P}})$ if and only if $\pi_P \circ f \in B_1(X)$ for all $P \in \mathcal{P}$.*

Proof. Only one implication needs a proof. Suppose that $\pi_P \circ f \in B_1(X)$ for all $P \in \mathcal{P}$. Let V be a basic open subset of $\mathbb{R}^{\mathcal{P}}$. That is, there exists a finite $\mathcal{P}' \subseteq \mathcal{P}$ such that $V = \bigcap_{P \in \mathcal{P}'} \pi_P^{-1}[U_P]$ where U_P is open in $\mathbb{R}$. Finally,

$$f^{-1}[V] = \bigcap_{P \in \mathcal{P}'} (\pi_P \circ f)^{-1}[U_P]$$

is an F_σ set. Since $\mathcal{P}$ is countable, $\mathbb{R}^{\mathcal{P}}$ is second countable so every open set U in $\mathbb{R}^{\mathcal{P}}$ is a countable union of basic open sets. Hence, $f^{-1}[U]$ is F_σ. $\square$

Below we consider $\mathcal{P}$ with the discrete topology. For each $f : X \to \mathbb{R}^{\mathcal{P}}$ denote $\hat{f}(P, x) := \pi_P \circ f(x)$ for all $(P, x) \in \mathcal{P} \times X$. Similarly, for each $g : \mathcal{P} \times X \to \mathbb{R}$ denote $\check{g}(x)(P) := g(P, x)$. Given $A \subseteq (\mathbb{R}^{\mathcal{P}})^X$, we denote $\hat{A}$ as the set of all $\hat{f}$ such that $f \in A$.

The map $(\mathbb{R}^{\mathcal{P}})^X \to \mathbb{R}^{\mathcal{P} \times X}$ given by $f \mapsto \hat{f}$ is a homeomorphism and its inverse is given by $g \mapsto \check{g}$.

Lemma 2.7. *Let X be a Polish space and $\mathcal{P}$ be countable. Then, $f \in B_1(X, \mathbb{R}^{\mathcal{P}})$ if and only if $\hat{f} \in B_1(\mathcal{P} \times X)$.*

Proof. ($\Rightarrow$) Given an open set of reals U, we have that for every $P \in \mathcal{P}$, $f^{-1}[\pi_P^{-1}[U]]$ is F_σ by Lemma 2.6. Given that $\mathcal{P}$ is a discrete countable space, we observe that

$$\hat{f}^{-1}[U] = \bigcup_{P \in \mathcal{P}} \left(\{P\} \times f^{-1}[\pi_P^{-1}[U]] \right)$$

is also an F_σ set. ($\Leftarrow$) By lemma 2.6 it suffices to show that $\pi_P \circ f \in B_1(X)$ for all $P \in \mathcal{P}$. Fix an open $U \subseteq \mathbb{R}$. Write $\hat{f}^{-1}[U] = \bigcup_{n \in \mathbb{N}} F_n$ where F_n is closed in $\mathcal{P} \times X$. Then,

$$(\pi_P \circ f)^{-1}[U] = \bigcup_{n \in \mathbb{N}} \{x \in X : (P, x) \in F_n\}$$

which is F_σ. $\square$

We now direct our attention to a notion of the NIP that is more general than the one from the introduction. It can be interpreted as a sort of continuous version of the one presented in the preceding section.

Definition 2.8. We say that $A \subseteq \mathbb{R}^X$ has the *Non-Independence Property* (NIP) if and only if for every $\{f_n\}_{n \in \mathbb{N}} \subseteq A$ and for every $a < b$ there are finite disjoint sets $E, F \subseteq \mathbb{N}$ such that

$$\bigcap_{n \in E} f_n^{-1}(-\infty, a] \cap \bigcap_{n \in F} f_n^{-1}[b, \infty) = \emptyset.$$

Note that if X is compact and $A \subseteq C_p(X)$, then A has the NIP if and only if for every $\{f_n\}_{n \in \mathbb{N}} \subseteq A$ and for every $a < b$ there is $I \subseteq \mathbb{N}$ such that

$$\bigcap_{n \in I} f_n^{-1}(-\infty, a] \cap \bigcap_{n \notin I} f_n^{-1}[b, \infty) = \emptyset.$$

Given $A \subseteq Y^X$ and $K \subseteq X$ we write $A|_K := \{f|_K : f \in A\}$, i.e., the set of all restrictions of functions in A to K. The following Theorem is a slightly more general version of Theorem 2.5.

Theorem 2.9. *Assume that $\mathcal{P}$ is countable, X is a Polish space, and $A \subseteq C_p(X, \mathbb{R}^{\mathcal{P}})$ is such that $\pi_P \circ A$ is pointwise bounded for all $P \in \mathcal{P}$. The following are equivalent for every compact $K \subseteq X$:*

    (1) $\overline{A|_K} \subseteq B_1(K, \mathbb{R}^{\mathcal{P}})$.

    (2) $\pi_P \circ A|_K$ has the NIP for every $P \in \mathcal{P}$.

Proof. (1)$\Rightarrow$(2). Let $P \in \mathcal{P}$. Fix $\{f_n\}_{n \in \mathbb{N}} \subseteq A$ and $a < b$. By (1) we have that $\overline{A|_K} \subseteq B_1(K, \mathbb{R}^{\mathcal{P}})$. Applying the homeomorphism $f \mapsto \hat{f}$ and using lemma 2.7 we get $\overline{\hat{A}|_{\mathcal{P} \times K}} \subseteq B_1(\mathcal{P} \times K)$. By Theorem 2.5, there is $I \subseteq \mathbb{N}$ such that

$$(\mathcal{P} \times K) \cap \bigcap_{n \in I} \hat{f_n}^{-1}(-\infty, a] \cap \bigcap_{n \notin I} \hat{f_n}^{-1}[b, \infty) = \emptyset$$

Hence,

$$K \cap \bigcap_{n \in I} (\pi_P \circ f_n)^{-1}(-\infty, a] \cap \bigcap_{n \notin I} (\pi_P \circ f_n)^{-1}[b, \infty) = \emptyset$$

By compactness, there are finite $E \subseteq I$ and $F \subseteq \mathbb{N} \setminus I$ such that

$$K \cap \bigcap_{n \in E} (\pi_P \circ f_n)^{-1}(-\infty, a] \cap \bigcap_{n \in F} (\pi_P \circ f_n)^{-1}[b, \infty) = \emptyset$$

Thus, $\pi_P \circ A|_L$ has the NIP.

    (2)$\Rightarrow$(1) Fix $f \in \overline{A|_K}$. By lemma 2.6 it suffices to show that $\pi_P \circ f \in B_1(K)$ for all $P \in \mathcal{P}$. By (2), $\pi_P \circ A|_K$ has the NIP. Hence, by Theorem 2.5 we have $\overline{\pi_P \circ A|_K} \subseteq B_1(K)$. But then $\pi_P \circ f \in \overline{\pi_P \circ A|_K} \subseteq B_1(K)$. $\qquad\square$

Lastly, a simple but significant result that helps understand the operation of restricting a set of functions to a specific subspace of the domain space X, of course in the context of the NIP, is that we may always assume that said subspace is closed. Concretely, whether we take its closure or not has no effect on the NIP:

Lemma 2.10. *Assume that X is Hausdorff and that $A \subseteq C_p(X)$. The following are equivalent for every $L \subseteq X$:*

    (i) A_L has the NIP.

    (ii) $A|_{\overline{L}}$ has the NIP.

Proof. It suffices to show that (i)$\Rightarrow$(ii). Suppose that (ii) does not hold, i.e., that there are $\{f_n\}_{n \in \mathbb{N}} \subseteq A$ and $a < b$ such that for all finite disjoint $E, F \subseteq \mathbb{N}$:

$$\overline{L} \cap \bigcap_{n \in E} f_n^{-1}(-\infty, a] \cap \bigcap_{n \in F} f_n^{-1}[b, \infty) \neq \emptyset.$$

Pick $a' < b'$ such that $a < a' < b' < b$. Then, for any finite disjoint $E, F \subseteq \mathbb{N}$ we can choose

$$x \in \overline{L} \cap \bigcap_{n \in E} f_n^{-1}(-\infty, a') \cap \bigcap_{n \in F} f_n^{-1}(b', \infty)$$

By definition of closure:

$$L \cap \bigcap_{n \in E} f_n^{-1}(-\infty, a'] \cap \bigcap_{n \in F} f_n^{-1}[b', \infty) \neq \emptyset.$$

This contradicts (i). $\qquad\square$

252   3. NIP in the context of Compositional Computation Structures

253   In this section, we study what the NIP tell us in the context of deep compu-
254   tations as defined in [ADIW24]. We say a structure $(L, \mathcal{P}, \Gamma)$ is a *Compositional*
255   *Computation Structure* (CCS) if $L \subseteq \mathbb{R}^{\mathcal{P}}$ is a subspace of $\mathbb{R}^{\mathcal{P}}$, with the pointwise
256   convergence topology, and $\Gamma \subseteq L^L$ is a semigroup under composition. The motiva-
257   tion for CCS comes from (continuous) model theory, where $\mathcal{P}$ is a fixed collection
258   of predicates and L is a (real-valued) structure. Every point in L is identified with
259   its "type", which is the tuple of all values the point takes on the predicates from
260    $\mathcal{P}$, i.e., an element of $\mathbb{R}^{\mathcal{P}}$. In this context, elements of $\mathcal{P}$ are called *features*. In the
261   discrete model theory framework, one views the space of complete-types as a sort of
262   compactification of the structure L. In this context, we don't want to consider only
263   points in L (realized types) but in its closure $\overline{L}$ (possibly unrealized types). The
264   problem is that the closure $\overline{L}$ is not necessarily compact, an assumption that turns
265   out to be very useful in the context of continuous model theory. To bypass this
266   problem in a framework for deep computations, Alva, Dueñez, Iovino and Walton
267   introduced in [ADIW24] the concept of *shards*, which essentially consists in cover-
268   ing (a large fragment) of the space $\overline{L}$ by compact, and hence pointwise-bounded,
269   subspaces (shards). We shall give the formal definition next.

270   A *sizer* is a tuple $r_\bullet = (r_P)_{P \in \mathcal{P}}$ of positive real numbers indexed by $\mathcal{P}$. Given a
271   sizer $r_\bullet$, we define the $r_\bullet$-*shard* as:

$$L[r_\bullet] = L \cap \prod_{P \in \mathcal{P}} [-r_P, r_P]$$

272   For an illustrative example, we can frame Newton's polynomial root approxima-
273   tion method in the context of a CCS (see Example 5.6 of [ADIW24] for details) as
274   follows. Begin by considering the extended complex numbers $\hat{\mathbb{C}} := \mathbb{C} \cup \{\infty\}$ with
275   the usual Riemann sphere topology that makes it into a compact space (where
276   unbounded sequences converge to ∞). In fact, not only is this space compact
277   but it is covered by the shard given by the sizer $(1, 1, 1)$ (the unit sphere is con-
278   tained in the cube $[-1, 1]^3$). The space $\hat{\mathbb{C}}$ is homeomorphic to the usual unit
279   sphere $S^2 := \{(x, y, z) : x^2 + y^2 + z^2 = 1\}$ of $\mathbb{R}^3$, by means of the stereographic
280   projection and its inverse $\hat{\mathbb{C}} \to S^2$. This function is regarded as a triple of pred-
281   icates $x, y, z : \hat{\mathbb{C}} \to [-1, 1]$ where each will map an extended complex number to
282   its corresponding real coordinate on the cube $[-1, 1]^3$. Now fix the cubic com-
283   plex polynomial $p(s) := s^3 - 1$, and consider the map which performs one step
284   in Newton's method at a particular (extended) complex number s, for finding
285   a root of p, $\gamma_p : \hat{\mathbb{C}} \to \hat{\mathbb{C}}$. The explicit inner workings of γ_p are irrelevant for
286   this example, except for the fact that it is a continuous mapping. It follows that
287    $(S^2, \{x, y, z\}, \{\gamma_p^k : k \in \mathbb{N}\})$ is a CCS. The idea is that repeated applications of
288    $\gamma_p(s), \gamma_p \circ \gamma_p(s), \gamma_p \circ \gamma_p \circ \gamma_p(s), \ldots$ would approximate a root of p provided s was
289   a good enough initial guess.

290   The $r_\bullet$-type-shard is defined as $\mathcal{L}[r_\bullet] = \overline{L[r_\bullet]}$ and $\mathcal{L}_{sh}$ is the union of all type-
291   shards. Notice that $\mathcal{L}_{sh}$ is not necessarily equal to $\mathcal{L} = \overline{L}$, unless $\mathcal{P}$ is countable
292   (see [ADIW24]). A *transition* is a map $f : L \to L$, in particular, every element
293   in the semigroup Γ is a transition (these are called *realized computations*). In
294   practice, one would like to work with "definable" computations, i.e., ones that can
295   be described by a computer. In this topological framework, being continuous is an
296   expected requirement. However, as in the case of complete-types in model theory,

we will work with "unrealized computations", i.e., maps $f : \mathcal{L}_{\mathrm{sh}} \to \mathcal{L}_{\mathrm{sh}}$. Note that continuity of a computation does not imply that it can be continuously extended to $\mathcal{L}_{\mathrm{sh}}$.

Suppose that a transition map $f : L \to \mathcal{L}$ can be extended continuously to a map $\mathcal{L} \to \mathcal{L}$. Then, the Stone-Weierstrass theorem implies that the feature $\pi_P \circ f$ (here P is a fixed predicate, and the feature is hence continuous) can be uniformly approximated by polynomials on the compact set $\mathcal{L}[r_\bullet]$. Theorem 2.2 in [ADIW24] formalizes the converse of this fact, in the sense that transitions maps that are not continuously extendable in this fashion cannot be obtained from simple constructions involving predicates. Under this framework, the features $\pi_P \circ f$ of such transitions f are not approximable by polynomials, and so they are understood as "non-computable" since, again, we expect the operations computers carry out to be determined by elementary algebra corresponding to polynomials (namely addition and multiplication). Therefore it is crucial we assume some extendibility conditions.

We say that the CCS $(L, \mathcal{P}, \Gamma)$ satisfies the *Extendibility Axiom* if for all $\gamma \in \Gamma$, there is $\tilde{\gamma} : \mathcal{L}_{\mathrm{sh}} \to \mathcal{L}_{\mathrm{sh}}$ such that for every sizer $r_\bullet$ there is an $s_\bullet$ such that $\tilde{\gamma}|_{\mathcal{L}[r_\bullet]} : \mathcal{L}[r_\bullet] \to \mathcal{L}[s_\bullet]$ is continuous. For a deeper discussion about this axiom, we refer the reader to [ADIW24].

A collection R of sizers is called *exhaustive* if $\mathcal{L}_{\mathrm{sh}} = \bigcup_{r_\bullet \in R} \mathcal{L}[r_\bullet]$. We say that $\Delta \subseteq \Gamma$ is R-*confined* if $\gamma|_{L[r_\bullet]} : L[r_\bullet] \to L[r_\bullet]$ for every $r_\bullet \in R$ and $\gamma \in \Delta$. Elements in Δ are called *real-valued computations* (in this article we will refer to them simply as *computations*) and elements in $\overline{\Delta} \subseteq \mathcal{L}_{\mathrm{sh}}^L$ are called (real-valued) *deep computations* or *ultracomputations*. By $\tilde{\Delta}$ we denote the set of all extensions $\tilde{\gamma}$ for $\gamma \in \Delta$. For a more complete description of this framework, we refer the reader to [ADIW24].

3.1. **NIP and Baire-1 definability of deep computations.** Under what conditions are deep computations Baire class 1, and thus well-behaved according to our framework, on type-shards? The next Theorem says that, again under the assumption that $\mathcal{P}$ is countable, the space of deep computations is a Rosenthal compactum (when restricted to shards) if and only if the set of computations has the NIP on features. Hence, we can import the theory of Rosenthal compacta into this framework of deep computations.

Theorem 3.1. *Let* $(L, \mathcal{P}, \Gamma)$ *be a CCS satisfying the Extendibility Axiom with* $\mathcal{P}$ *countable. Let* R *be an exhaustive collection of sizers. Let* $\Delta \subseteq \Gamma$ *be* R-*confined. The following are equivalent.*

(1) $\overline{\tilde{\Delta}|_{\mathcal{L}[r_\bullet]}} \subseteq B_1(\mathcal{L}[r_\bullet], \mathcal{L}[r_\bullet])$ *for all* $r_\bullet \in R$.

(2) $\pi_P \circ \Delta|_{L[r_\bullet]}$ *has the NIP for all* $P \in \mathcal{P}$ *and* $r_\bullet \in R$, *that is, for all* $P \in \mathcal{P}$, $r_\bullet \in R$, $a < b$, $\{\gamma_n\}_{n \in \mathbb{N}} \subseteq \Delta$ *there are finite disjoint* $E, F \subseteq \mathbb{N}$ *such that*

$$L[r_\bullet] \cap \bigcap_{n \in E} (\pi_P \circ \gamma_n)^{-1}(-\infty, a] \cap \bigcap_{n \in F} (\pi_P \circ \gamma_n)^{-1}[b, \infty) = \emptyset.$$

Moreover, if any (hence all) of the preceding conditions hold, then every deep computation $f \in \overline{\Delta}$ *can be extended to a Baire-1 function on shards, i.e., there is* $\tilde{f} : \mathcal{L}_{\mathrm{sh}} \to \mathcal{L}_{\mathrm{sh}}$ *such that* $\tilde{f}|_{\mathcal{L}[r_\bullet]} \in B_1(\mathcal{L}[r_\bullet], \mathcal{L}[r_\bullet])$ *for all* $r_\bullet \in R$. *In particular, on each shard every deep computation is the pointwise limit of a countable sequence of computations.*

Proof. Since $\mathcal{P}$ is countable, then $\mathcal{L}[r_\bullet] \subseteq \mathbb{R}^{\mathcal{P}}$ is Polish. Also, the Extendibility Axiom implies that $\pi_P \circ \tilde{\Delta}|_{\mathcal{L}[r_\bullet]}$ is a pointwise bounded set of continuous functions

for all $P \in \mathcal{P}$. Hence, Theorem 2.9 and Lemma 2.10 prove the equivalence of (1) and (2). If (1) holds and $f \in \overline{\Delta}$, then write $f = \mathcal{U}\lim_i \gamma_i$ as an ultralimit. Define $\tilde{f} := \mathcal{U}\lim_i \tilde{\gamma}_i$. Hence, for all $r_\bullet \in R$ we have $\tilde{f}|_{\mathcal{L}[r_\bullet]} \in \overline{\tilde{\Delta}}|_{\mathcal{L}[r_\bullet]} \subseteq B_1(\mathcal{L}[r_\bullet], \mathcal{L}[r_\bullet])$. That every deep computation is a pointwise limit of a countable sequence of computations follows from the fact that for a Polish space X every compact subset of $B_1(X)$ is Fréchet-Urysohn (that is, a space where topological closures coincide with sequential closures, see Theorem 3F in [BFT78] or Theorem 4.1 in [Deb13]). $\qquad\square$

Given a countable set Δ of computations satisfying the NIP on features and shards (condition (2) of Theorem 3.1) we have that $\overline{\tilde{\Delta}}_{\mathcal{L}[r_\bullet]}$ (for a fixed sizer $r_\bullet$) is a separable *Rosenthal compactum* (compact subset of $B_1(P \times \mathcal{L}[r_\bullet])$. The work of Todorčević ([Tod99]) and Argyros, Dodos, Kanellopoulos ([ADK08]) culminates in a trichotomy theorem for separable Rosenthal Compacta. Inspired by the work of Glasner and Megrelishvili ([GM22]), we are interested to see how this allows us to classify and obtain different levels of PAC-learnability (NIP).

Recall that a topological space X is *hereditarily separable* (HS) if every subspace is separable and that X is *first countable* if every point in X has a countable local basis. Every separable metrizable space is hereditarily separable and it is a result of R. Pol that every hereditarily separable Rosenthal compactum is first countable (see section 10 in [Deb13]). This suggests the following definition:

Definition 3.2. Let $(L, \mathcal{P}, \Gamma)$ be a CCS satisfying the Extendibility Axiom and R be an exhaustive collection of sizers. Let $\Delta \subseteq \Gamma$ be an R-confined countable set of computations satisfying the NIP on shards and features (condition (2) in Theorem 3.1). We say that Δ is:

  (i) NIP_1 if $\overline{\tilde{\Delta}}|_{\mathcal{L}[r_\bullet]}$ is first countable for every $r_\bullet \in R$.

  (ii) NIP_2 if $\overline{\tilde{\Delta}}|_{\mathcal{L}[r_\bullet]}$ is hereditarily separable for every $r_\bullet \in R$.

  (iii) NIP_3 if $\overline{\tilde{\Delta}}|_{\mathcal{L}[r_\bullet]}$ is metrizable for every $r_\bullet \in R$.

Observe that $\text{NIP}_3 \Rightarrow \text{NIP}_2 \Rightarrow \text{NIP}_1 \Rightarrow \text{NIP}$. A natural question that would continue this work is to find examples of CCS that separate these levels of NIP. In [Tod99], Todorčević isolates 3 canonical examples of Rosenthal compacta that witness the failure of the converse implications above. We now present some separable and non-separable examples of Rosenthal compacta:

  (1) *Alexandroff compactification of a discrete space of size continuum.* For each $a \in 2^{\mathbb{N}}$ consider the map $\delta_a : 2^{\mathbb{N}} \to \mathbb{R}$ given by $\delta_a(x) = 1$ if $x = a$ and $\delta_a(x) = 0$ otherwise. Let $A(2^{\mathbb{N}}) = \{\delta_a : a \in 2^{\mathbb{N}}\} \cup \{0\}$, where 0 is the zero map. Notice that $A(2^{\mathbb{N}})$ is a compact subset of $B_1(2^{\mathbb{N}})$, in fact $\{\delta_a : a \in 2^{\mathbb{N}}\}$ is a discrete subspace of $B_1(2^{\mathbb{N}})$ and its pointwise closure is precisely $A(2^{\mathbb{N}})$. Hence, this is a Rosenthal compactum which is not first countable. Notice that this space is also not separable.
  (2) *Extended Alexandroff compactification.* For each finite binary sequence $s \in 2^{<\mathbb{N}}$, let $\nu_s : 2^{\mathbb{N}} \to \mathbb{R}$ be given by $\nu_s(x) = 1$ if x extends s and $\nu_s(x) = 0$ otherwise. Let $\hat{A}(2^{\mathbb{N}})$ be the pointwise closure of $\{\nu_s : s \in 2^{<\mathbb{N}}\}$, i.e., $\hat{A}(2^{\mathbb{N}}) = A(2^{\mathbb{N}}) \cup \{\nu_s : s \in 2^{<\mathbb{N}}\}$. Note that this space is a separable Rosenthal compactum which is not first countable.
  (3) *Split Cantor.* Let $<$ be the lexicographic order in the space of infinite binary sequences, i.e., $2^{\mathbb{N}}$. For each $a \in 2^{\mathbb{N}}$ let $f_a^- : 2^{\mathbb{N}} \to \mathbb{R}$ be given by

$f_a^-(x) = 1$ if $x < a$ and $f_a^-(x) = 0$ otherwise. Let $f_a^+ : 2^{\mathbb{N}} \to \mathbb{R}$ be given by $f_a^+(x) = 1$ if $x \le a$ and $f_a^+(x) = 0$ otherwise. The split Cantor is the space $S(2^{\mathbb{N}}) = \{f_a^- : a \in 2^{\mathbb{N}}\} \cup \{f_a^+ : a \in 2^{\mathbb{N}}\}$. This is a separable Rosenthal compactum. One example of a countable dense subset is the set of all f_a^+ and f_a^- where a is an infinite binary sequence that is eventually constant. Moreover, it is hereditarily separable but it is not metrizable.

(4) *Alexandroff Duplicate.* Let K be any compact metric space and consider the Polish space $X = C(K) \sqcup K$, i.e., the disjoint union of $C(K)$ (with its supremum norm topology) and K. For each $a \in K$ define $g_a^0, g_a^1 : X \to \mathbb{R}$ as follows:

$$g_a^0(x) = \begin{cases} x(a), & x \in C(K) \\ 0, & x \in K \end{cases}$$

$$g_a^1(x) = \begin{cases} x(a), & x \in C(K) \\ \delta_a(x), & x \in K \end{cases}$$

Let $D(K) = \{g_a^0 : a \in K\} \cup \{g_a^1 : a \in K\}$. Notice that $D(K)$ is a first countable Rosenthal compactum. It is not separable if K is uncountable. The interesting case will be when $K = 2^{\mathbb{N}}$.

(5) *Extended Alexandroff Duplicate of the split Cantor.* For each finite binary sequence $t \in 2^{<\mathbb{N}}$ let $a_t \in 2^{\mathbb{N}}$ be the sequence starting with t and ending with 0's and let $b_t \in 2^{\mathbb{N}}$ be the sequence starting with t and ending with 1's. Define $h_t : 2^{\mathbb{N}} \to \mathbb{R}$ by
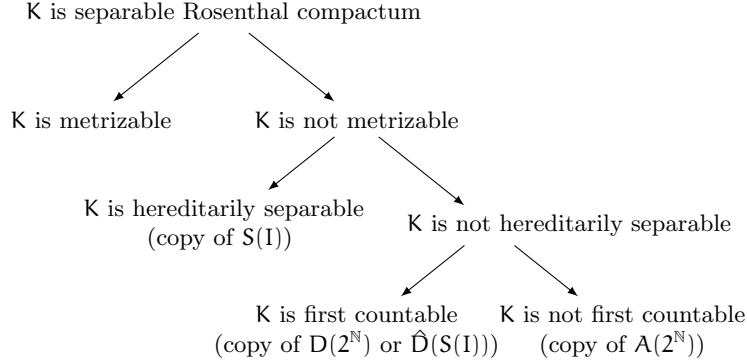
$$h_t(x) = \begin{cases} 0, & x < a_t \\ 1/2, & a_t \le x \le b_t \\ 1, & b_t < x \end{cases}$$

Let $\hat{D}(S(2^{\mathbb{N}}))$ be the pointwise closure of the set $\{h_t : t \in 2^{<\mathbb{N}}\}$. Hence, $\hat{D}(S(2^{\mathbb{N}}))$ is a separable first countable Rosenthal compactum which is not hereditarily separable. In fact, it contains an uncountable discrete subspace (see Theorem 5 in [Tod99]).

Theorem 3.3 (Todorčević's Trichotomy, [Tod99], Theorem 3 in [ADK08])**.** *Let* K *be a separable Rosenthal Compactum.*

   (i) If K *is hereditarily separable but non-metrizable, then* $S(2^{\mathbb{N}})$ *embeds into* K.
   (ii) If K *is first countable but not hereditarily separable, then either* $D(2^{\mathbb{N}})$ *or* $\hat{D}(S(2^{\mathbb{N}}))$ *embeds into* K.
   (iii) If K *is not first countable, then* $A(2^{\mathbb{N}})$ *embeds into* K.

In other words, we have the following classification:

K is separable Rosenthal compactum

K is metrizable   K is not metrizable

K is hereditarily separable
(copy of $S(I)$)   K is not hereditarily separable

K is first countable   K is not first countable
(copy of $D(2^{\mathbb{N}})$ or $\hat{D}(S(I))$)   (copy of $A(2^{\mathbb{N}})$)

Lastly, the definitions provided here for NIP_i ($i = 1, 2, 3$) are topological.

Question 3.4. Is there a non-topological characterization for NIP_i, $i = 1, 2, 3$?

More can be said about the nature of the embeddings in Todorčević's Trichotomy. Given a separable Rosenthal compactum K, there is typically more than one countable dense subset of K. We can view a separable Rosenthal compactum as the accumulation points of a countable family of pointwise bounded real-valued functions. The choice of the countable families is not important when a bijection between them can be lifted to a homeomorphism of their closures. To be more precise:

Definition 3.5. Given a Polish space X, a countable set I and two pointwise bounded families $\{f_i : i \in I\} \subseteq \mathbb{R}^X$, $\{g_i : i \in I\} \subseteq \mathbb{R}^X$ indexed by I. We say that $\{f_i : i \in I\}$ and $\{g_i : i \in I\}$ are *equivalent* if and only if the map $f_i \mapsto g_i$ is extended to a homeomorphism from $\overline{\{f_i : i \in I\}}$ to $\overline{\{g_i : i \in I\}}$.

Notice that in the separable examples discussed before ($\hat{A}(2^{\mathbb{N}})$, $S(2^{\mathbb{N}})$ and $\hat{D}(S(2^{\mathbb{N}}))$) the countable dense subsets are indexed by the binary tree $2^{<\mathbb{N}}$. This choice of index is useful because the Ramsey theory of perfect subsets of the Cantor space $2^{\mathbb{N}}$ can be imported to analyze the behavior of the accumulation points. Since $2^{<\mathbb{N}}$ is countable, we can always choose this index for the countable dense subsets. This is done in [ADK08].

Definition 3.6. Given a Polish space X and a pointwise bounded family $\{f_t : t \in 2^{<\mathbb{N}}\}$. We say that $\{f_t : t \in 2^{<\mathbb{N}}\}$ is *minimal* if and only if for every dyadic subtree $\{s_t : t \in 2^{<\mathbb{N}}\}$ of $2^{<\mathbb{N}}$, $\{f_{s_t} : t \in 2^{<\mathbb{N}}\}$ is equivalent to $\{f_t : t \in 2^{<\mathbb{N}}\}$.

One of the main results in [ADK08] is that there are (up to equivalence) seven minimal families of Rosenthal compacta and that for every relatively compact $\{f_t : t \in 2^{<\mathbb{N}}\} \subseteq B_1(X)$ there is a dyadic subtree $\{s_t : t \in 2^{<\mathbb{N}}\}$ such that $\{f_{s_t} : t \in 2^{<\mathbb{N}}\}$ is equivalent to one of the minimal families. We shall describe the minimal families next. We will follow the same notation as in [ADK08]. For any node $t \in 2^{<\mathbb{N}}$, we denote by $t^\frown 0^\infty$ ($t^\frown 1^\infty$) the infinite binary sequence starting with t and ending in 0's (1's). Fix a regular dyadic subtree $R = \{s_t : t \in 2^{<\mathbb{N}}\}$ of $2^{<\mathbb{N}}$ (i.e., a dyadic subtree such that every level of R is contained in a level of $2^{<\mathbb{N}}$) with the property that for all $s, s' \in R$, $s^\frown 0^\infty \neq s'^\frown 0^\infty$ and $s^\frown 1^\infty \neq s'^\frown 1^\infty$. Given $t \in 2^{<\mathbb{N}}$, let v_t be the characteristic function of the set $\{x \in 2^{\mathbb{N}} : x \text{ extends } t\}$. Let $<$ be the lexicographic order in $2^{\mathbb{N}}$. Given $a \in 2^{\mathbb{N}}$, let $f_a^+ : 2^{\mathbb{N}} \to \{0, 1\}$ be the characteristic function of $\{x \in 2^{\mathbb{N}} : a \leq x\}$ and let $f_a^- : 2^{\mathbb{N}} \to \{0, 1\}$ be the characteristic function of

$\{x \in 2^{\mathbb{N}} : a < x\}$. Given two maps $f, g : 2^{\mathbb{N}} \to \mathbb{R}$ we denote by $(f, g) : 2^{\mathbb{N}} \sqcup 2^{\mathbb{N}} \to \mathbb{R}$ the function which is f on the first copy of $2^{\mathbb{N}}$ and g on the second copy of $2^{\mathbb{N}}$.

(1) $D_1 = \{\frac{1}{|t|+1}\nu_t : t \in 2^{<\mathbb{N}}\}$. This is discrete in $\overline{D_1} = A(2^{\mathbb{N}})$.

(2) $D_2 = \{s_t^\frown 0^\infty : t \in 2^{<\mathbb{N}}\}$. This is discrete in $\overline{D_2} = 2^{\leq \mathbb{N}}$.

(3) $D_3 = \{f_{s_t^\frown 0^\infty}^+ : t \in 2^{<\mathbb{N}}\}$. This is a discrete in $\overline{D_3} = S(2^{\mathbb{N}})$.

(4) $D_4 = \{f_{s_t^\frown 1^\infty}^- : t \in 2^{<\mathbb{N}}\}$. This is discrete in $\overline{D_4} = S(2^{\mathbb{N}})$.

(5) $D_5 = \{\nu_t : t \in 2^{<\mathbb{N}}\}$. This is discrete in $\overline{D_5} = \hat{A}(2^{\mathbb{N}})$.

(6) $D_6 = \{(\nu_{s_t}, s_t^\frown 0^\infty) : t \in 2^{<\mathbb{N}}\}$. This is discrete in $\overline{D_6} = \hat{D}(2^{\mathbb{N}})$.

(7) $D_7 = \{(\nu_{s_t}, x_{s_t^\frown 0^\infty}^+) : t \in 2^{<\mathbb{N}}\}$. This is discrete in $\overline{D_7} = \hat{D}(S(2^{\mathbb{N}}))$

Theorem 3.7 (Heptacotomy of minimal families, Theorem 2 in [ADK08])**.** *Let X be Polish. For every relatively compact $\{f_t : t \in 2^{<\mathbb{N}}\} \subseteq B_1(X)$, there exists $i = 1, 2, \ldots, 7$ and a regular dyadic subtree $\{s_t : t \in 2^{<\mathbb{N}}\}$ of $2^{<\mathbb{N}}$ such that $\{f_{s_t} : t \in 2^{<\mathbb{N}}\}$ is equivalent to D_i. Moreover, all D_i are minimal and mutually non-equivalent.*

3.2. **NIP and definability by universally measurable functions.** We now turn to the question: what happens when $\mathcal{P}$ is uncountable? Notice that the countability assumption is crucial in the proof of Theorem 2.9 essentially because it makes $\mathbb{R}^{\mathcal{P}}$ a Polish space. For the uncountable case, we may lose Baire-1 definability so we shall replace $B_1(X)$ by a bigger class. Recall that the purpose of studying the class of Baire-1 functions is that a pointwise limit of continuous functions is not necessarily continuous. In [BFT78], J. Bourgain, D.H. Fremlin and M. Talagrand characterized the Non-Independence Property of a set of continuous functions with various notions of compactness in function spaces containing $C(X)$, such as $B_1(X)$. In this section we will replace $B_1(X)$ with the larger space $M_r(X)$ of universally measurable functions. The development of this section is based on Theorem 2F in [BFT78]. We now give the relevant definitions. Readers with little familiarity with measure theory can review the appendix for standard definitions appearing in this subsection.

Given a Hausdorff space X and a measurable space (Y, Σ), we say that $f : X \to Y$ is *universally measurable* (with respect to Σ) if $f^{-1}(E)$ is universally measurable for every $E \in \Sigma$, i.e., $f^{-1}(E)$ is μ-measurable for every Radon probability measure μ on X. When $Y = \mathbb{R}$ we will always take $\Sigma = \mathcal{B}(\mathbb{R})$, the Borel σ-algebra of $\mathbb{R}$. In that case, a function $f : X \to \mathbb{R}$ is universally measurable if and only if $f^{-1}(U)$ is μ-measurable for every Radon probability measure μ on X and every open set $U \subseteq \mathbb{R}$. Following [BFT78], the collection of all universally measurable real-valued functions will be denoted by $M_r(X)$. In the context of deep computations, we will be interested in transition maps from a state space $L \subseteq \mathbb{R}^{\mathcal{P}}$ to itself. There are two natural σ-algebras one can consider in the product space $\mathbb{R}^{\mathcal{P}}$: the Borel σ-algebra, i.e., the σ-algebra generated by open sets in $\mathbb{R}^{\mathcal{P}}$; and the cylinder σ-algebra, i.e., the σ-algebra generated by Borel cylinder sets or equivalently basic open sets in $\mathbb{R}^{\mathcal{P}}$. Note that when $\mathcal{P}$ is countable, both σ-algebras coincide but in general the cylinder σ-algebra is strictly smaller. We will use the cylinder σ-algebra to define universally measurable maps $f : \mathbb{R}^{\mathcal{P}} \to \mathbb{R}^{\mathcal{P}}$. The reason for this choice is because of the following characterization:

Lemma 3.8. *Let X be a Hausdorff space and $Y = \prod_{i \in I} Y_i$ be any product of measurable spaces (Y_i, Σ_i) for $i \in I$. Let Σ_Y be the cylinder σ-algebra generated by the measurable spaces (Y_i, Σ_i). Let $f : X \to Y$. The following are equivalent:*

484   (i) $f : X \to Y$ *is universally measurable (with respect to Σ_Y).*
485   (ii) $\pi_i \circ f : X \to Y_i$ *is universally measurable (with respect to Σ_i) for all $i \in I$.*

486 *Proof.* (i)$\Rightarrow$(ii) is clear since the projection maps π_i are measurable and the com-
487 position of measurable functions is measurable. To prove (ii)$\Rightarrow$(i), suppose that
488 $C = \prod_{i \in I} C_i$ is a measurable cylinder and let J be the finite set of $i \in I$ such that
489 $C_i \neq Y_i$. Then, $C = \bigcap_{i \in J} \pi_i^{-1}(C_i)$ so $f^{-1}(C) = \bigcap_{i \in J}(\pi_i \circ f)^{-1}(C_i)$ is a universally
490 measurable set by assumption.   □

491   The previous lemma says that a transition map is universally measurable if and
492 only if it is universally measurable on all its features. In other words, we can check
493 measurability of a transition just by checking measurability in all its features. We
494 will denote by $M_r(X, \mathbb{R}^{\mathcal{P}})$ the collection of all universally measurable functions
495 $f : X \to \mathbb{R}^{\mathcal{P}}$ (with respect to the cylinder σ-algebra), endowed with the topology of
496 pointwise convergence.

497 **Definition 3.9.** Let $(L, \mathcal{P}, \Gamma)$ be a CCS. We say that a transition $f : L \to L$ is
498 *universally measurable shard-definable* if and only if there exists $\tilde{f} : \mathcal{L}_{sh} \to \mathcal{L}_{sh}$
499 extending f such that for every sizer $r_\bullet$ there is a sizer $s_\bullet$ such that the restriction
500 $\tilde{f}|_{\mathcal{L}[r_\bullet]} : \mathcal{L}[r_\bullet] \to \mathcal{L}[s_\bullet]$ is universally measurable, i.e. $\pi_P \circ \tilde{f}|_{\mathcal{L}[r_\bullet]} : \mathcal{L}[r_\bullet] \to [-s_P, s_P]$
501 is μ-measurable for every Radon probability measure μ on $\mathcal{L}[r_\bullet]$.

502   We will need the following result about NIP and universally measurable func-
503 tions:

504 **Theorem 3.10** (Bourgain-Fremlin-Talagrand, Theorem 2F in [BFT78]). *Let X be a*
505 *Hausdorff space and $A \subseteq C(X)$ be pointwise bounded. The following are equivalent:*

506   *(i) $\overline{A} \subseteq M_r(X)$.*
507   *(ii) For every compact $K \subseteq X$, $A|_K$ has the NIP.*
508   *(iii) For every Radon measure μ on X, A is relatively countably compact in*
509   *$\mathcal{L}^0(X, \mu)$, i.e., every countable subset of A has an accumulation point in*
510   *$\mathcal{L}^0(X, \mu)$.*

511   Theorem 2.5 immediately yields the following.

512 **Theorem 3.11.** *Let $(L, \mathcal{P}, \Gamma)$ be a CCS satisfying the Extendibility Axiom. Let R*
513 *be an exhaustive collection of sizers. Let $\Delta \subseteq \Gamma$ be R-confined. If $\pi_P \circ \Delta|_{L[r_\bullet]}$ has*
514 *the NIP for all $P \in \mathcal{P}$ and all $r_\bullet \in R$, then every deep computation is universally*
515 *measurable shard-definable.*

516 *Proof.* By the Extendibility Axiom, Theorem 2.5 and lemma 2.10 we have that
517 $\overline{\pi_P \circ \tilde{\Delta}|_{\mathcal{L}[r_\bullet]}} \subseteq M_r(\mathcal{L}[r_\bullet])$ for all $r_\bullet \in R$ and $P \in \mathcal{P}$. Let $f \in \overline{\Delta}$ be a deep computation.
518 Write $f = \mathcal{U} \lim_i \gamma_i$ as an ultralimit of computations in Δ. Define $\tilde{f} := \mathcal{U} \lim_i \tilde{\gamma}_i$.
519 Then, for all $r_\bullet \in R$ and $P \in \mathcal{P}$ $\pi_P \circ \tilde{\gamma}_i|_{\mathcal{L}[r_\bullet]} \in M_r(\mathcal{L}[r_\bullet])$ for all i so $\pi_P \circ f|_{\mathcal{L}[r_\bullet]} \in$
520 $\overline{\pi_P \circ \tilde{\Delta}|_{\mathcal{L}[r_\bullet]}} \subseteq M_r(\mathcal{L}[r_\bullet])$.   □

521 **Question 3.12.** Under the same assumptions of the previous Theorem, suppose
522 that every deep computation of Δ is universally measurable shard-definable. Must
523 $\pi_P \circ \Delta|_{L[r_\bullet]}$ have the NIP for all $P \in \mathcal{P}$ and all $r_\bullet \in R$?

3.3. **Talagrand stability and definability by universally measurable functions.** There is another notion closely related to NIP, introduced by Talagrand in [Tal84] while studying Pettis integration. Suppose that X is a compact Hausdorff space and $A \subseteq \mathbb{R}^X$. Let μ be a Radon probability measure on X. Given a μ-measurable set $E \subseteq X$, a positive integer k and real numbers $a < b$. we write:

$$D_k(A, E, a, b) = \bigcup_{f \in A} \{x \in E^{2k} : f(x_{2i}) \le a,\ f(x_{2i+1}) \ge b\ \text{ for all } i < k\}$$

We say that A is *Talagrand μ-stable* if and only if for every μ-measurable set $E \subseteq X$ of positive measure and for every $a < b$ there is $k \ge 1$ such that $(\mu^{2k})^*(D_k(A, E, a, b)) < (\mu(E))^{2k}$. Notice that we work with the outer measure because it is not necessarily true that the sets $D_k(A, E, a, b)$ are μ-measurable. This is certainly the case when A is a countable set of continuous (or μ-measurable) functions.

The following lemma establishes that Talagrand stability is a way to ensure that deep computations are definable by measurable functions. We include the proof for the reader's convenience.

Lemma 3.13. *If A is Talagrand μ-stable, then $\overline{A}$ is also Talagrand μ-stable and $\overline{A} \subseteq \mathcal{L}^0(X, \mu)$.*

Proof. First, observe that a subset of a μ-stable set is μ-stable. To show that $\overline{A}$ is μ-stable, observe that $D_k(\overline{A}, E, a, b) \subseteq D_k(A, E, a', b')$ where $a < a' < b' < b$ and E is a μ-measurable set with positive measure. It suffices to show that $\overline{A} \subseteq \mathcal{L}^0(X, \mu)$. Suppose that there exists $f \in \overline{A}$ such that $f \notin \mathcal{L}^0(X, \mu)$. By a characterization of measurable functions (see 413G in [Fre03]), there exists a μ-measurable set E of positive measure and $a < b$ such that $\mu^*(P) = \mu^*(Q) = \mu(E)$ where $P = \{x \in E : f(x) \le a\}$ and $Q = \{x \in E : f(x) \ge b\}$. Then, for any $k \ge 1$: $(P \times Q)^k \subseteq D_k(\{f\}, E, a, b)$ so $(\mu^{2k})^*(D_k(\{f\}, E, a, b)) = (\mu^*(P)\mu^*(Q))^k = (\mu(E))^{2k}$. Thus, $\{f\}$ is not μ-stable, but we argued before that a subset of a μ-stable set must be μ-stable. $\square$

We say that A is *universally Talagrand stable* if A is Talagrand μ-stable for every Radon probability measure μ on X. A similar argument as before, yields the following:

Theorem 3.14. *Let $(L, \mathcal{P}, \Gamma)$ be a CCS satisfying the Extendibility Axiom. If $\pi_P \circ \Delta|_{L[r_\bullet]}$ is universally Talagrand stable for all $P \in \mathcal{P}$ and all sizers $r_\bullet$, then every deep computation is universally measurable sh-definable.*

It is then natural to ask: what is the relationship between Talagrand stability and the NIP? The following dichotomy will be useful.

Lemma 3.15 (Fremlin's Dichotomy, 463K in [Fre03])**.** *If (X, Σ, μ) is a perfect σ-finite measure space (in particular, for X compact and μ a Radon probability measure on X) and $\{f_n : n \in \mathbb{N}\}$ be a sequence of real-valued measurable functions on X, then either:*

 (i) $\{f_n : n \in \mathbb{N}\}$ has a subsequence that converges μ-almost everywhere, or
 (ii) $\{f_n : n \in \mathbb{N}\}$ has a subsequence with no μ-measurable accumulation point in $\mathbb{R}^X$.

The preceding lemma can be considered as the measure theoretic version of Rosenthal's Dichotomy. Combining this dichotomy with the Theorem 3.10 we get the following result:

Theorem 3.16. *Let* X *be a Hausdorff space and* $A \subseteq C(X)$ *be pointwise bounded. The following are equivalent:*

(i) $\overline{A} \subseteq M_r(X)$.

(ii) *For every compact* $K \subseteq X$, $A|_K$ *has the NIP.*

(iii) *For every Radon measure* μ *on* X, A *is relatively countably compact in* $\mathcal{L}^0(X, \mu)$, *i.e., every countable subset of* A *has an accumulation point in* $\mathcal{L}^0(X, \mu)$.

(iv) *For every Radon measure* μ *on* X *and every sequence* $\{f_n : n \in \mathbb{N}\} \subseteq A$, *there is a subsequence that converges* μ*-almost everywhere.*

Proof. Notice that the equivalence (i)-(iii) is Theorem 3.10. Notice that the equivalence of (iii) and (iv) is Fremlin's Dichotomy Theorem. $\square$

Lemma 3.17. *Let* X *be a compact Hausdorff space and* $A \subseteq C(X)$ *be pointwise bounded. If* A *is universally Talagrand stable, then* A *has the NIP.*

Proof. By Theorem 3.10, it suffices to show that A is relatively countably compact in $\mathcal{L}^0(X, \mu)$ for all Radon probability measure μ on X. Since A is Talagrand μ-stable for any such μ, then $\overline{A} \subseteq \mathcal{L}^0(X, \mu)$. In particular, A is relatively countably compact in $\mathcal{L}^0(X, \mu)$. $\square$

Question 3.18. Is the converse true?

There is a delicate point in this question, as it may be sensitive to set-theoretic axioms (even assuming countability of A).

Theorem 3.19 (Talagrand, Theorem 9-3-1(a) in [Tal84]). *Let* X *be a compact Hausdorff space and* $A \subseteq M_r(X)$ *be countable and pointwise bounded. Assume that* $[0, 1]$ *is not the union of* $< \mathfrak{c}$ *closed measure zero sets. If* A *has the NIP, then* A *is universally Talagrand stable.*

Theorem 3.20 (Fremlin, Shelah, [FS93]). *It is consistent that there exists a countable pointwise bounded set of Lebesgue measurable functions with the NIP which is not Talagrand stable with respect to Lebesgue measure.*

Appendix: Measure Theory

Given a set X, a collection Σ of subsets of X is called a σ-*algebra* if Σ contains X and is closed under complements and countable unions. Hence, for example, a σ-algebra is also closed under countable intersections. Intuitively, a σ-algebra is a collection of sets in which we can define a σ-additive measure. We call sets in a σ-algebra Σ *measurable sets* and the pair (X, Σ) a measurable space. If X is a topological space, there is a natural σ-algebra of subsets of X, namely the *Borel* σ-*algebra* $\mathcal{B}(X)$, i.e., the smallest σ-algebra containing all open subsets of X. Given two measurable spaces (X, Σ_X) and (Y, Σ_Y), we say that a function $f : X \to Y$ is *measurable* if and only if $f^{-1}(E) \in \Sigma_X$ for every $E \in \Sigma_Y$. In particular, we say that $f : X \to \mathbb{R}$ is measurable if $f^{-1}(E) \in \Sigma_X$ for all $E \in \mathcal{B}(\mathbb{R})$ (equivalently, E open in $\mathbb{R}$).

Given a measurable space (X, Σ), a σ-*additive measure* is a non-negative function $\mu : \Sigma \to \mathbb{R}$ with the property that $\mu(\emptyset) = 0$ and $\mu(\bigcup_{n=0}^{\infty} A_n) = \sum_{n=0}^{\infty} \mu(A_n)$ whenever $\{A_n : n \in \mathbb{N}\} \subseteq \Sigma$ is pairwise disjoint. We call (X, Σ, μ) a *measure space*. A σ-additive measure is called a *probability measure* if $\mu(X) = 1$. A measure μ is *complete* if for every $A \subseteq B \in \Sigma$, $\mu(B) = 0$ implies $A \in \Sigma$. In words, subsets of measure-zero sets are always measurable (and hence, by the monotonicity of μ, have measure zero as well). A measure μ is σ-*finite* if $X = \cup_{n=1}^{\infty} X_n$ where $\mu(X_n) < \infty$ for all $n \in \mathbb{N}$ (i.e., X can be decomposed into countably many finite measure sets). A measure μ is *perfect* if for every measurable $f : X \to \mathbb{R}$ and every measurable set E with $\mu(E) > 0$, there exists a compact $K \subseteq f(E)$ such that $\mu(f^{-1}(K)) > 0$. We say that a property $\phi(x)$ about $x \in X$ holds μ-*almost everywhere* if $\mu(\{x \in X : \phi(x) \text{ does not hold}\}) = 0$.

A special example of the preceding concepts is that of a *Radon measure*. If X is a Hausdorff topological space, then a measure μ on the Borel sets of X is called a *Radon measure* if

- for every open set U, $\mu(U)$ is the supremum of $\mu(K)$ over all compact $K \subseteq U$, that is, the measure of open sets may be approximated via compact sets; and
- every point of X has a neighborhood $U \ni x$ for which $\mu(U)$ is finite.

Perhaps the most famous example of a Radon measure on $\mathbb{R}$ is the Lebesgue measure of Borel sets. If X is finite, $\mu(A) := |A|$ (the cardinality of A) defines a Radon measure on X. Every Radon measure is perfect (see 451A, 451B and 451C in [Fre03]).

While not immediately obvious, sets can be measurable according to one measure, but non-measurable according to another. Given a measure space (X, Σ, μ) we say that a set $E \subseteq X$ is μ-*measurable* if there are $A, B \in \Sigma$ such that $A \subseteq E \subseteq B$ and $\mu(B \backslash A) = 0$. The set of all μ-measurable sets is a σ-algebra containing Σ and it is denoted by Σ_{μ}. A set $E \subseteq X$ is *universally measurable* if it is μ-measurable for every Radon probability measure on X. It follows that Borel sets are universally measurable. We say that $f : X \to \mathbb{R}$ is μ-*measurable* if $f^{-1}(E) \in \Sigma_{\mu}$ for all $E \in \mathcal{B}(\mathbb{R})$ (equivalently, E open in $\mathbb{R}$). The set of all μ-measurable functions is denoted by $\mathcal{L}^0(X, \mu)$.

Recall that if $\{X_i : i \in I\}$ is a collection of topological spaces indexed by some set I, then the product space $X := \prod_{i \in I} X_i$ is endowed with the topology generated by *cylinders*, that is, sets of the form $\prod_{i \in I} U_i$ where each U_i is open in X_i, and $U_i = X_i$ except for finitely many indices $i \in I$. If each space is measurable, say we pair X_i with a σ-algebra Σ_i, then there are multiple ways to interpret the product space X as a measurable space, but the interpretation we care about in this paper is the so called *cylinder* σ-*algebra*, as used in Lemma 3.8. Namely, let Σ be the σ-algebra generated by sets of the form

$$\prod_{i \in I} C_i, \quad C_i \in \Sigma_i, \ C_i = X_i \text{ for all but finitely many } i \in I.$$

We remark that when I is uncountable and $\Sigma_i = \mathcal{B}(X_i)$ for all $i \in I$, then Σ is, in general, strictly **smaller** than $\mathcal{B}(X)$.

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