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# COMPLEXITY OF DEEP COMPUTATIONS VIA TOPOLOGY OF FUNCTION SPACES

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ABSTRACT. We study complexity of deep computations. We use topology of function spaces, specifically, the classification Rosenthal compacta, to identify new complexity classes. We use the language of model theory, specifically, the concept of the independence from Shelah’s classification theory, to translate between topology and computation.

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## 0. INTRODUCTION

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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], among others). In this paper, we combine ideas of topology, measure theory, and model theory to study these limit phenomena from a unified viewpoint.

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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 Todorćević [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].

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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 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 Todorćević, from the late 90s, for functions of the first Baire class [Tod99].

Todorćević’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 that 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. Todorćević’s trichotomy has been utilized to settle longstanding problems in topological dynamics and topological entropy [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 Todorćević’s trichotomy, we invoke a more recent heptachotomy for Rosenthal compacta obtained by Argyros, Dodos and Kanellopoulos [ADK08]. Argyros, Dodos and Kanellopoulos identified seven 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 and measure theory. The necessary topological background beyond undergraduate topology is covered in section 1.

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.

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## 1. GENERAL TOPOLOGICAL PRELIMINARIES: FROM CONTINUITY TO BAIRE CLASS 1

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  $F_\sigma$  if it is a countable union of closed sets, and  $G_\delta$  if it is a countable intersection of closed sets. Note that in a metrizable space, every open set is  $F_\sigma$ ; equivalently, every closed set is  $G_\delta$ .

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

129 products of Polish spaces are Polish; this includes spaces like  $\mathbb{R}^{\mathbb{N}}$ , the space of  
 130 sequences of real numbers.

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

136 The following result is a cornerstone of descriptive set theory, closely tied to the  
 137 work of Waclaw Sierpiński and Kazimierz Kuratowski, with proofs often built upon  
 138 their foundations and formalized later, notably, involving Stefan Mazurkiewicz’s  
 139 work on complete metric spaces.

140 **Fact 1.1.** *A subset  $A$  of a Polish space  $X$  is itself Polish in the subspace topology*  
 141 *if and only if it is a  $G_\delta$  set. In particular, closed subsets and open subsets of Polish*  
 142 *spaces are also Polish spaces.*

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

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

161 A topological space  $X$  is *perfectly normal* if it is normal and every closed subset  
 162 of  $X$  is a  $G_\delta$  (equivalently, every open subset of  $X$  is a  $G_\delta$ ). Note that every  
 163 metrizable space is perfectly normal.

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

166 **Fact 1.2** (Baire). *If  $X$  is perfectly normal, then the following conditions are equiv-*  
 167 *alent for a function  $f : X \rightarrow \mathbb{R}$ :*

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

172 Moreover, if  $X$  is Polish and  $f \notin B_1(X)$ , then there exists countable  $D_0, D_1 \subseteq X$   
 173 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) 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 1.3.** *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.* Since  $A$  is pointwise bounded, for each  $x \in X$ , fix  $M_x > 0$  such that  $|f(x)| \leq M_x$  for every  $f \in A$ .

(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 1.2, 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  $\lim_{n \rightarrow \infty} f_n(x) = f(x)$  for all  $x \in D_0 \cup D_1$ . Indeed, use the countability to enumerate  $D_0 \cup D_1$  as  $\{x_n\}_{n \in \mathbb{N}}$ . Then for each positive  $n$  find  $f_n \in A$  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  $D_0 \cup D_1$ ,  $g$  does not have a point of continuity on the closed set  $\overline{D_0} = \overline{D_1}$ , which contradicts Fact 1.2.

(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  $\prod_{x \in X} [-M_x, M_x]$ ; Tychonoff's theorem states that the product of compact spaces is always compact, and since closed subsets of compact spaces are compact,  $\overline{A}$  must be compact, as desired.  $\square$

**1.1. From Rosenthal's dichotomy to the Bourgain-Fremlin-Talagrand dichotomy to Shelah's NIP.** In metrizable spaces, points of closure of some subset can always be approximated by points inside the set, via a convergent sequence. For more complicated spaces, such as  $C_p(X)$ , this fails in remarkable ways. To see an example, consider the Cantor space  $X = 2^{\mathbb{N}}$ , and for each  $n \in \mathbb{N}$  define  $p_n : X \rightarrow \{0, 1\}$  by  $p_n(x) = x(n)$  for each  $x \in X$ . Then  $p_n$  is continuous for each  $n$ , but one can show (see Chapter 1.1 of [Tod97] for details) that the only continuous functions in the closure of  $\{p_n\}_{n \in \mathbb{N}}$  are the functions  $p_n$  themselves; moreover, none of the subsequences of  $\{p_n\}_{n \in \mathbb{N}}$  converge. In some sense, this example is the worst possible scenario for convergence. The topological space obtained from this closure is well-known: it is the *Stone-Ćech compactification* of the discrete space of natural numbers, or  $\beta\mathbb{N}$  for short, and it is an important object of study in general topology.

The following theorem, established by Haskell Rosenthal in 1974, is fundamental in functional analysis, and describes a sharp division in the behavior of sequences within a Banach space:

**Theorem 1.4** (Rosenthal’s Dichotomy, [Ros74]). *If  $X$  is Polish and  $\{f_n\} \subseteq C_p(X)$  is pointwise bounded, then either  $\{f_n\}_{n \in \mathbb{N}}$  contains a convergent subsequence or a subsequence whose closure (in  $\mathbb{R}^X$ ) is homeomorphic to  $\beta\mathbb{N}$ .*

In other words, a pointwise bounded set of continuous functions either contains a convergent subsequence, or a subsequence whose closure is essentially the same as the example mentioned in the previous paragraphs (the “wildest” possible scenario). Note that in the preceding example, the functions are trivially pointwise bounded in  $\mathbb{R}^X$  as the functions can only take values 0 and 1.

The genesis of Theorem 1.4 was Rosenthal’s  $\ell_1$  theorem, which states that the only reason why Banach space can fail to have an isomorphic copy of  $\ell_1$  (the space of absolutely summable sequences) is the presence of a bounded sequence with no weakly Cauchy subsequence. The theorem is famous for connecting diverse areas of mathematics, namely, Banach space geometry, Ramsey theory, set theory, and topology of function spaces.

As we move from  $C_p(X)$  to the larger space  $B_1(X)$ , we find a similar dichotomy. Either every point of closure of the set of functions will be a Baire class 1 function, or there is a sequence inside the set that behaves in the wildest possible way. The theorem is usually not phrased as a dichotomy but rather as an equivalence:

**Theorem 1.5** (The BFT Dichotomy. Bourgain-Fremlin-Talagrand, [BFT78, Theorem 4G]). *Let  $X$  be a Polish space and  $A \subseteq C_p(X)$  be pointwise bounded. The following are equivalent:*

- (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 every  $a < b$  there is  $I \subseteq \mathbb{N}$  such that

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

**Definition 1.6.** We shall say that a set  $A \subseteq \mathbb{R}^X$  satisfies the *Independence Property*, or IP for short, if it satisfies the following condition: There exists every  $\{f_n\}_{n \in \mathbb{N}} \subseteq A$  and  $a < b$  such that for every pair of disjoint sets  $E, F \subseteq \mathbb{N}$ , we have

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

If  $A$  satisfies the negation of this condition, we will say that  $A$  *satisfies NIP*, or that has the NIP.

*Remark 1.7.* Note that if  $X$  is compact and  $A \subseteq C_p(X)$ , then  $A$  satisfies 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

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

To summarize, the particular case of Theorem 1.8 for  $X$  compact can be stated in the following way:

**Theorem 1.8.** *Let  $X$  be a compact Polish space. Then, for every pointwise bounded  $A \subseteq C_p(X)$ , one and exactly one of the following two conditions must hold:*

- (i)  $\overline{A} \subseteq B_1(X)$ .
- (ii)  $A$  has NIP.

253 The Independence Property was first isolated by Saharon Shelah in model theory  
 254 as a dividing line between theories whose models are “tame” (corresponding to  
 255 NIP) theories of models are “wild” (corresponding to IP). See [She71, Definition  
 256 4.1],[She90]. We will discuss this dividing line in more detail in the next section.

257 **1.2. NIP as universal dividing line between polynomial and exponential**  
 258 **complexity.** The particular case of the BFT Dichotomy (Theorem 1.8) when  $A$   
 259 consists of  $\{0, 1\}$ -valued (i.e.,  $\{\text{Yes}, \text{No}\}$ -valued) strings was discovered indepen-  
 260 dently, around 1971-1972 in many foundational contexts related to polynomial  
 261 (“tame”) vs exponential (“wild”) complexity: In model theory, by Saharon She-  
 262 lah [She71],[She90], in combinatorics, by Norbert Sauer [Sau72], and Shelah [She72,  
 263 She90], and in statistical learning, by Vladimir Vapnik and Alexey Chervonenkis [VC71,  
 264 VC74].

265 **In model theory:** Shelah’s classification theory is a foundational program  
 266 in mathematical logic devised to categorize first-order theories based on  
 267 the complexity and structure of their models. A theory  $T$  is considered  
 268 classifiable in Shelah’s sense if the number of non-isomorphic models of  $T$   
 269 of a given cardinality can be described by a bounded number of numerical  
 270 invariants. In contrast, a theory  $T$  is unclassifiable if the number of models  
 271 of  $T$  of a given cardinality is the maximum possible number. The number  
 272 of models of  $T$  is directly impacted by the number of “types” over of pa-  
 273 rameters in models of  $T$ ; a controlled number of types is a characteristic of  
 274 a classifiable theory.

275 In Shelah’s classification program [She90], theories without the indepen-  
 276 dence property (called NIP theories, or dependent theories) have a well-  
 277 behaved, “tame” structure; the number of types over a set of parameters  
 278 of size  $\kappa$  of such a theory is of polynomially or similar “slow” growth on  $\kappa$ .  
 279 In contrast, Theories with the Independence Property (called IP theories)  
 280 are considered “intractable” or “wild”. A theory with the Independence  
 281 Property produces the maximum possible number of types over a set of  
 282 parameters; for a set of parameters of cardinality  $\kappa$ , the theory will have  
 283  $2^{2^\kappa}$ -many distinct types.

284 **In combinatorics:** Sauer [Sau72] and Shelah [She72] proved the following:  
 285 If  $\mathcal{F} = \{S_0, S_1, \dots\}$  is a family of subsets of some infinite set  $S$ , then  
 286 either for every  $n \in \mathbb{N}$ , there is either a set  $A \subseteq S$  with  $|A| = n$  such that  
 287  $|\{S_i \cap A : i \in \mathbb{N}\}| = 2^n$  (yielding exponential complexity), or there exists  
 288  $N \in \mathbb{N}$  such that for every  $A \subseteq S$  with  $|A| \geq N$ , one has

$$|\{S_i \cap A : i \in \mathbb{N}\}| \leq \sum_{i=0}^{N-1} \binom{|A|}{i} \approx O(|A|^N)$$

289 (yielding polynomial complexity). This answered a question of Erdős.

290 **In machine learning:** Readers familiar with statistical learning may rec-  
 291 ognize the Sauer-Shelah lemma as the dichotomy discovered and proved  
 292 slightly earlier (1971) by Vapnik and Chervonenkis [VC71, VC74] to ad-  
 293 dress the problem of uniform convergence in statistics. The least integer  
 294  $N$  given by the preceding paragraph, when it exists, is called the *VC-*  
 295 *dimension* of  $\mathcal{F}$ . This is a core concept in machine learning. If such an  
 296 integer  $N$  does not exist, we say that the VC-dimension of  $\mathcal{F}$  is infinite. The

lemma provides upper bounds on the number of data points (sample size  $m$ ) needed to learn a concept class with VC dimension  $d \in \mathbb{N}$  by showing this number grows polynomially with  $m$  and  $d$  (namely,  $\sum_{i=0}^d \binom{m}{i} \approx O(m^d)$ ), not exponentially. The Fundamental Theorem of Statistical Learning states that a hypothesis class is PAC-learnable (PAC stands for “Probably Approximately Correct”) if and only if its VC dimension is finite.

**1.3. Rosenthal compacta.** The comprehensiveness of Theorem 1.8, attested by the examples outlined in the preceding section, led to the following definition (isolated by Gilles Godefroy [God80]):

**Definition 1.9.** A Rosenthal compactum is a compact Hausdorff topological space  $K$  that can be topologically embedded as a compact subset into the space of all functions of the first Baire class on some Polish space  $X$ , equipped with the topology of pointwise convergence.

Rosenthal compacta are characterized by significant topological and dynamical tameness properties. They play an important role in functional analysis, measure theory, dynamical systems, descriptive set theory, and model theory. In this paper, we introduce their applicability in deep computation. For this, we shall first focus on countable languages, which is the theme of the next subsection.

**1.4. The special case  $B_1(X, \mathbb{R}^{\mathcal{P}})$  with  $\mathcal{P}$  countable.** Our goal now is to characterize relatively compact subsets of  $B_1(X, Y)$  for the particular case when  $Y = \mathbb{R}^{\mathcal{P}}$  with  $\mathcal{P}$  countable. Given  $P \in \mathcal{P}$  we denote the projection map onto the  $P$ -coordinate by  $\pi_P : \mathbb{R}^{\mathcal{P}} \rightarrow \mathbb{R}$ . From a high-level topological interpretation, the next lemma states that, in this context, the spaces  $\mathbb{R}$  and  $\mathbb{R}^{\mathcal{P}}$  are really not that different, and that if we understand the Baire class 1 functions of one space, then we also understand the functions of both.

**Lemma 1.10.** *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  $\mathbb{R}$ . Then,

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

is an  $F_\sigma$  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  $F_\sigma$ .  $\square$

Below we consider  $\mathcal{P}$  with the discrete topology. For each  $f : X \rightarrow \mathbb{R}^{\mathcal{P}}$  denote  $\hat{f}(P, x) := \pi_P \circ f(x)$  for all  $(P, x) \in \mathcal{P} \times X$ . Similarly, for each  $g : \mathcal{P} \times X \rightarrow \mathbb{R}$  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  $f \in A$ . Note that the map  $(\mathbb{R}^{\mathcal{P}})^X \rightarrow \mathbb{R}^{\mathcal{P} \times X}$  given by  $f \mapsto \hat{f}$  is a homeomorphism and its inverse is given by  $g \mapsto \check{g}$ .

**Lemma 1.11.** *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.* ( $\Rightarrow$ ) By Lemma 1.10, given an open set of reals  $U$ , we have  $f^{-1}[\pi_P^{-1}[U]]$  is  $F_\sigma$  for every  $P \in \mathcal{P}$ . Given that  $\mathcal{P}$  is a discrete countable space, we observe that

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

333 is an  $F_\sigma$  as well.

( $\Leftarrow$ ) By lemma 1.10 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,

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

334 which is  $F_\sigma$ . □

335 Given  $A \subseteq Y^X$  and  $K \subseteq X$  we write  $A|_K := \{f|_K : f \in A\}$ , i.e., the set of  
336 all restrictions of functions in  $A$  to  $K$ . The following Theorem is a slightly more  
337 general version of Theorem 1.8.

338 **Theorem 1.12.** *Assume that  $\mathcal{P}$  is countable,  $X$  is a Polish space, and  $A \subseteq$   
339  $C_p(X, \mathbb{R}^{\mathcal{P}})$  is such that  $\pi_P \circ A$  is pointwise bounded for all  $P \in \mathcal{P}$ . The follow-  
340 ing are equivalent for every compact  $K \subseteq X$ :*

- 341 (1)  $\overline{A|_K} \subseteq B_1(K, \mathbb{R}^{\mathcal{P}})$ .  
342 (2)  $\pi_P \circ A|_K$  satisfies 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  $\overline{A|_K} \subseteq B_1(K, \mathbb{R}^{\mathcal{P}})$ . Applying the homeomorphism  $f \mapsto \hat{f}$  and using lemma 1.11 we get  $\hat{A}|_{\mathcal{P} \times K} \subseteq B_1(\mathcal{P} \times K)$ . By Theorem 1.8, 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 the compactness of  $K$ , there are finite  $E \subseteq I$  and  $F \subseteq \mathbb{N} \setminus I$  such that

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

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

344 (2) $\Rightarrow$ (1) Fix  $f \in \overline{A|_K}$ . By lemma 1.10 it suffices to show that  $\pi_P \circ f \in B_1(K)$   
345 for all  $P \in \mathcal{P}$ . By (2),  $\pi_P \circ A|_K$  satisfies the NIP. Hence, by Theorem 1.8 we have  
346  $\overline{\pi_P \circ A|_K} \subseteq B_1(K)$ . But then  $\pi_P \circ f \in \overline{\pi_P \circ A|_K} \subseteq B_1(K)$ . □

347 Lastly, a simple but useful lemma that helps understand when we restrict a set  
348 of functions to a specific subspace of the domain space, we may always assume that  
349 the subspace is closed, as replacing the subspace by its closure has no effect on NIP.

350 **Lemma 1.13.** *Assume that  $X$  is Hausdorff and that  $A \subseteq C_p(X)$ . The following  
351 are equivalent for every  $L \subseteq X$ :*

- 352 (i)  $A_L$  satisfies the NIP.  
353 (ii)  $A|_{\overline{L}}$  satisfies 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  $E, F \subseteq \mathbb{N}$ :

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

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

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

By definition of closure:

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

354 This contradicts (i). □

## 355 2. COMPOSITIONAL COMPUTATION STRUCTURES.

356 In this section, we connect function spaces with floating point computation. We  
357 start by summarizing some basic concepts from [ADIW24].

358 A *computation states structure* is a pair  $(L, \mathcal{P})$ , where  $L$  is a set whose elements we  
359 call *states* and  $\mathcal{P}$  is a collection of real-valued functions on  $L$  that we call *predicates*.  
360 For a state  $v \in L$ , *type* of  $v$  is defined as the indexed family

$$\text{tp}(v) = (P(v))_{P \in \mathcal{P}} \in \mathbb{R}^{\mathcal{P}}.$$

361 For each  $P \in \mathcal{P}$ , we call real value  $P(v)$  the  $P$ -th *feature* of  $v$ . A *transition* of a  
362 computation states structure  $(L, \mathcal{P})$  is a map  $f : L \rightarrow L$ .

363 Intuitively,  $L$  is the set of states of a computation, and the predicates  $P \in \mathcal{P}$   
364 are primitives that are given and accepted as computational. We think of each  
365 state  $v \in L$  as being uniquely characterized by its type  $\text{tp}(v)$ . Thus, in practice,  
366 we identify  $L$  with a subset of  $\mathbb{R}^{\mathcal{P}}$ . A typical case will be when  $L = \mathbb{R}^{\mathbb{N}}$  or  $L = \mathbb{R}^n$   
367 for some positive integer  $n$  and there is a predicate  $P_i(v) = v_i$  for each of the  
368 coordinates  $v_i$  of  $v$ . We regard the space of types as a topological space, endowed  
369 with the topology of pointwise convergence inherited from  $\mathbb{R}^{\mathcal{P}}$ . In particular, for  
370 each  $P \in \mathcal{P}$ , the projection map  $v \mapsto P(v)$  is continuous.

371 **Definition 2.1.** Given a computation states structure  $(L, \mathcal{P})$ , any element of  $\mathbb{R}^{\mathcal{P}}$   
372 in the image of  $L$  under the map  $v \mapsto \text{tp}(v)$  will be called a *realized type*. The  
373 topological closure of the set of realized types in  $\mathbb{R}^{\mathcal{P}}$  (endowed with the point-  
374 wise convergence topology) will be called the *space of types* of  $(L, \mathcal{P})$ , denoted  $\mathcal{L}$ .  
375 Elements of  $\mathcal{L} \setminus L$  will be called *unrealized types*.

376 In traditional model theory, the space of types of a structure is viewed as a sort  
377 of compactification of the structure, and the compactness of type spaces plays a  
378 central role. However, the space  $\mathcal{L}$  defined above is not necessarily compact. To  
379 bypass this obstacle, we follow the idea introduced in [ADIW24] of covering  $\mathcal{L}$  by  
380 “thin” compact subspaces that we call *shards*. The formal definition of shard is  
381 next.

382 **Definition 2.2.** A *sizer* is a tuple  $r_{\bullet} = (r_P)_{P \in \mathcal{P}}$  of positive real numbers indexed  
383 by  $\mathcal{P}$ . Given a sizer  $r_{\bullet}$ , we define the  $r_{\bullet}$ -*shard* as:

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

For a sizer  $r_\bullet$ , the  $r_\bullet$ -type shard is defined as  $\mathcal{L}[r_\bullet] = \overline{L[r_\bullet]}$ . We define  $\mathcal{L}_{\text{sh}}$ , as the union of all type-shards.

**Definition 2.3.** A *Compositional Computation Structure* (CCS) is a triple  $(L, \mathcal{P}, \Gamma)$ , where

- $(L, \mathcal{P})$  is a computation states structure, and
- $\Gamma \subseteq L^L$  is a semigroup under composition.

The elements of the semigroup  $\Gamma$  are called the *computations* of the structure  $(L, \mathcal{P}, \Gamma)$ .

If  $\Delta \subseteq \Gamma$ , we say that  $\Delta \subseteq \Gamma$  is *R-confined* if  $\gamma|_{L[r_\bullet]} : L[r_\bullet] \rightarrow L[r_\bullet]$  for every  $r_\bullet \in R$  and  $\gamma \in \Delta$ . Elements in  $\overline{\Delta} \subseteq \mathcal{L}_{\text{sh}}$  are called (real-valued) *deep computations* or *ultracomputations*.

A tenet of our approach is that a map  $f : L \rightarrow \mathcal{L}$  is to be considered “effectively computable” if, for each  $Q \in \mathcal{P}$ , the output feature  $Q \circ f : L \rightarrow \mathbb{R}$  is a *definable* predicate in the following sense:

Given any arbitrary  $\varepsilon > 0$  and any  $K \subseteq L$  wherein every input feature  $P(v)$  remains bounded in magnitude there is an  $\varepsilon$ -approximating continuous “algebraic” operator  $\varphi(P_1, \dots, P_n)$  of finitely many input predicates  $P_1, \dots, P_n \in \mathcal{P}$ , such that the following holds: for all  $v \in K$ , the output feature  $Q(f(v))$  is  $\varepsilon$ -approximated by  $\varphi(P_1(v), \dots, P_n(v))$ . By “algebraic”, we mean that, aside from the primitives  $P_1, \dots, P_n$ , the approximating operator  $\varphi(P_1, \dots, P_n)$  uses only the algebra operations of  $\mathbb{R}^{\mathcal{P}}$ , i.e., vector addition, vector multiplication, and scalar addition.

It is shown in [ADIW24]) that:

- (1) For a definable  $f : L \rightarrow \mathcal{L}$ , the approximating operators  $\varphi$  may be taken to be *polynomials* of the input features, and
- (2) Definable transforms  $f : L \rightarrow \mathcal{L}$  are precisely those that extend to continuous  $\tilde{f} : \mathcal{L} \rightarrow \mathcal{L}$  (this is the property of *extendibility* mentioned above).

This motivates the following definition.

**Definition 2.4.** We say that a CCS  $(L, \mathcal{P}, \Gamma)$  satisfies the *Extendability Axiom* if for all  $\gamma \in \Gamma$ , there is  $\tilde{\gamma} : \mathcal{L}_{\text{sh}} \rightarrow \mathcal{L}_{\text{sh}}$  such that for every sizer  $r_\bullet$  there is a sizer  $s_\bullet$  such that  $\tilde{\gamma}|_{\mathcal{L}[r_\bullet]} : \mathcal{L}[r_\bullet] \rightarrow \mathcal{L}[s_\bullet]$  is continuous. We refer to  $\tilde{\gamma}$  as a *free* extension of  $\gamma$ .

By the preceding remarks, the Extendability Axiom says that the elements of the semigroup  $\Gamma$  are definable. For the rest of the paper, fix for each  $\gamma \in \Gamma$  a free extension  $\tilde{\gamma}$  of  $\gamma$ . For any  $\Delta \subseteq \Gamma$ , let  $\tilde{\Delta}$  denote  $\{\tilde{\gamma} : \gamma \in \Delta\}$ .

For a detailed discussion of the Extendability Axiom, we refer the reader to [ADIW24].

For an illustrative example, we can frame Newton’s polynomial root approximation method in the context of a CCS (see Example 5.6 of [ADIW24] for details) as follows. Begin by considering the extended complex numbers  $\hat{\mathbb{C}} := \mathbb{C} \cup \{\infty\}$  with the usual Riemann sphere topology that makes it into a compact space (where unbounded sequences converge to  $\infty$ ). In fact, not only is this space compact but it is covered by the shard given by the sizer  $(1, 1, 1)$  (the unit sphere is contained in the cube  $[-1, 1]^3$ ). The space  $\hat{\mathbb{C}}$  is homeomorphic to the usual unit sphere  $S^2 := \{(x, y, z) : x^2 + y^2 + z^2 = 1\}$  of  $\mathbb{R}^3$ , by means of the stereographic projection and its inverse  $\hat{\mathbb{C}} \rightarrow S^2$ . This function is regarded as a triple of predicates  $x, y, z : \hat{\mathbb{C}} \rightarrow [-1, 1]$  where each will map an extended complex number to

its corresponding real coordinate on the cube  $[-1, 1]^3$ . Now fix the cubic complex polynomial  $p(s) := s^3 - 1$ , and consider the map which performs one step in Newton's method at a particular (extended) complex number  $s$ , for finding a root of  $p$ ,  $\gamma_p : \hat{\mathbb{C}} \rightarrow \hat{\mathbb{C}}$ . The explicit inner workings of  $\gamma_p$  are irrelevant for this example, except for the fact that it is a continuous mapping. It follows that  $(S^2, \{x, y, z\}, \{\gamma_p^k : k \in \mathbb{N}\})$  is a CCS. The idea is that repeated applications of  $\gamma_p(s), \gamma_p \circ \gamma_p(s), \gamma_p \circ \gamma_p \circ \gamma_p(s), \dots$  would approximate a root of  $p$  provided  $s$  was a good enough initial guess.

437

### 3. CLASSIFYING DEEP COMPUTATIONS

**3.1. NIP, Rosenthal compacta, and deep computations.** Under what conditions are deep computations Baire class 1, and thus well-behaved according to our framework, on type-shards? The following theorem says that, 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 satisfies the NIP feature by feature. 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 compositional computational structure (Definition 2.3) satisfying the Extendability Axiom (Definition 2.4) with  $\mathcal{P}$  countable. Let  $R$  be an exhaustive collection of sizers. Let  $\Delta \subseteq \Gamma$  be  $R$ -confined. The following are equivalent.*

- (1)  $\overline{\Delta|_{\mathcal{L}[r_\bullet]}} \subseteq B_1(\mathcal{L}[r_\bullet], \mathcal{L}[r_\bullet])$  for all  $r_\bullet \in R$ .  
 (2)  $\pi_P \circ \Delta|_{\mathcal{L}[r_\bullet]}$  satisfies 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  $\tilde{f} : \mathcal{L}_{sh} \rightarrow \mathcal{L}_{sh}$  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,  $\mathcal{L}[r_\bullet] \subseteq \mathbb{R}^{\mathcal{P}}$  is Polish. Also, the Extendability 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 1.12 and Lemma 1.13 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]).  $\square$

**3.2. The Todorćević trichotomy and levels of PAC learnability.** Given a countable set  $\Delta$  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

467 *Rosenthal compactum* (see Definition 1.9). Todorčević proved a remarkable tri-  
 468 chotomy for Rosenthal compacta [Tod99], and later Argyros, Dodos, Kanellopou-  
 469 los [ADK08] proved an heptachotomy that refined Todorčević's classification. In  
 470 this section, inspired by the work of Glasner and Megrelishvili [GM22], we study  
 471 ways in which this classification allows us obtain different levels of PAC-learnability  
 472 and NIP.

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

478 **Definition 3.2.** Let  $(L, \mathcal{P}, \Gamma)$  be a CCS satisfying the Extendability Axiom and  $R$   
 479 be an exhaustive collection of sizers. Let  $\Delta \subseteq \Gamma$  be an  $R$ -confined countable set of  
 480 computations satisfying the NIP on shards and features (condition (2) in Theorem  
 481 3.1). We say that  $\Delta$  is:

- 482 (i) NIP<sub>1</sub> if  $\overline{\tilde{\Delta}|_{\mathcal{L}[r_\bullet]}}$  is first countable for every  $r_\bullet \in R$ .
- 483 (ii) NIP<sub>2</sub> if  $\overline{\tilde{\Delta}|_{\mathcal{L}[r_\bullet]}}$  is hereditarily separable for every  $r_\bullet \in R$ .
- 484 (iii) NIP<sub>3</sub> if  $\overline{\tilde{\Delta}|_{\mathcal{L}[r_\bullet]}}$  is metrizable for every  $r_\bullet \in R$ .

485 Observe that  $\text{NIP}_3 \Rightarrow \text{NIP}_2 \Rightarrow \text{NIP}_1 \Rightarrow \text{NIP}$ . A natural question that would con-  
 486 tinue this work is to find examples of CCS that separate these levels of NIP. In  
 487 [Tod99], Todorčević isolates three canonical examples of Rosenthal compacta that  
 488 witness the failure of the converse implications above.

489 We now present some separable and non-separable examples of Rosenthal com-  
 490 pacta:

### 491 Examples 3.3.

- 492 (1) *Alexandroff compactification of a discrete space of size continuum.* For  
 493 each  $a \in 2^{\mathbb{N}}$  consider the map  $\delta_a : 2^{\mathbb{N}} \rightarrow \mathbb{R}$  given by  $\delta_a(x) = 1$  if  $x = a$  and  
 494  $\delta_a(x) = 0$  otherwise. Let  $A(2^{\mathbb{N}}) = \{\delta_a : a \in 2^{\mathbb{N}}\} \cup \{0\}$ , where 0 is the zero  
 495 map. Notice that  $A(2^{\mathbb{N}})$  is a compact subset of  $B_1(2^{\mathbb{N}})$ , in fact  $\{\delta_a : a \in 2^{\mathbb{N}}\}$   
 496 is a discrete subspace of  $B_1(2^{\mathbb{N}})$  and its pointwise closure is precisely  $A(2^{\mathbb{N}})$ .  
 497 Hence, this is a Rosenthal compactum which is not first countable. Notice  
 498 that this space is also not separable.
- 499 (2) *Extended Alexandroff compactification.* For each finite binary sequence  $s \in$   
 500  $2^{<\mathbb{N}}$ , let  $v_s : 2^{\mathbb{N}} \rightarrow \mathbb{R}$  be given by  $v_s(x) = 1$  if  $x$  extends  $s$  and  $v_s(x) = 0$   
 501 otherwise. Let  $\hat{A}(2^{\mathbb{N}})$  be the pointwise closure of  $\{v_s : s \in 2^{<\mathbb{N}}\}$ , i.e.,  
 502  $\hat{A}(2^{\mathbb{N}}) = A(2^{\mathbb{N}}) \cup \{v_s : s \in 2^{<\mathbb{N}}\}$ . Note that this space is a separable  
 503 Rosenthal compactum which is not first countable.
- 504 (3) *Split Cantor.* Let  $<$  be the lexicographic order in the space of infinite  
 505 binary sequences, i.e.,  $2^{\mathbb{N}}$ . For each  $a \in 2^{\mathbb{N}}$  let  $f_a^- : 2^{\mathbb{N}} \rightarrow \mathbb{R}$  be given by  
 506  $f_a^-(x) = 1$  if  $x < a$  and  $f_a^-(x) = 0$  otherwise. Let  $f_a^+ : 2^{\mathbb{N}} \rightarrow \mathbb{R}$  be given  
 507 by  $f_a^+(x) = 1$  if  $x \leq a$  and  $f_a^+(x) = 0$  otherwise. The split Cantor is the  
 508 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  
 509 compactum. One example of a countable dense subset is the set of all  $f_a^+$   
 510 and  $f_a^-$  where  $a$  is an infinite binary sequence that is eventually constant.  
 511 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  $g_a^0, g_a^1 : X \rightarrow \mathbb{R}$  as follows:

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

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

512 Let  $D(K) = \{g_a^0 : a \in K\} \cup \{g_a^1 : a \in K\}$ . Notice that  $D(K)$  is a first  
 513 countable Rosenthal compactum. It is not separable if  $K$  is uncountable.  
 514 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  $h_t : 2^{\mathbb{N}} \rightarrow \mathbb{R}$  by

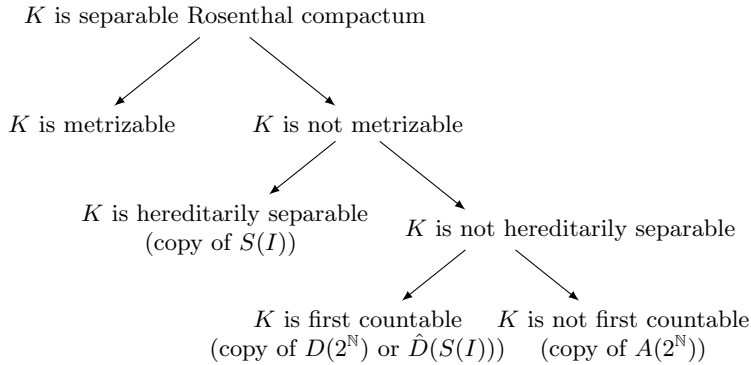
$$h_t(x) = \begin{cases} 0, & x < a_t \\ 1/2, & a_t \leq x \leq b_t \\ 1, & b_t < x \end{cases}$$

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

519 **Theorem 3.4** (Todorćević's Trichotomy, [Tod99], Theorem 3 in [ADK08]). *Let  $K$*   
 520 *be a separable Rosenthal Compactum.*

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

525 We thus have the following classification:



526

527 The definitions provided here for  $\text{NIP}_i$  ( $i = 1, 2, 3$ ) are topological. This raises  
 528 the following question:

529 **Question 3.5.** Is there a non-topological characterization for  $\text{NIP}_i$ ,  $i = 1, 2, 3$ ?

530 **3.3. The Argyros-Dodos-Kanellopoulos heptachotomy, and approxima-**  
 531 **bility of deep computation by minimal classes.** In the three separable three  
 532 cases given in 3.3, namely,  $(\hat{A}(2^{\mathbb{N}}), S(2^{\mathbb{N}}))$  and  $\hat{D}(S(2^{\mathbb{N}}))$ , the countable dense sub-  
 533 sets are indexed by the binary tree  $2^{<\mathbb{N}}$ . This choice of index is useful for two  
 534 reasons:

- 535 (1) Our emphasis is computational. Elements of  $2^{<\mathbb{N}}$  represent finite bitstrings,  
 536 i.e., standard computations, while Rosenthal compacta represent deep com-  
 537 putations, i.e., limits of finite computations. Mathematically, deep compu-  
 538 tations are pointwise limits of standard computations. However, compu-  
 539 tationally, we are interested in the manner (and the efficiency) in which the  
 540 approximations can occur.
- 541 (2) The Ramsey theory of perfect subsets of the Cantor space  $2^{\mathbb{N}}$  can be im-  
 542 ported to analyze the behavior of the accumulation points. Since  $2^{<\mathbb{N}}$  is  
 543 countable, we can always choose this index for the countable dense subsets.  
 544 This is done in [ADK08].

545 **Definition 3.6.** Let  $X$  be a Polish space.

- 546 (1) If  $I$  is a countable and  $\{f_i : i \in I\} \subseteq \mathbb{R}^X$ ,  $\{g_i : i \in I\} \subseteq \mathbb{R}^X$  are two  
 547 pointwise families by  $I$ , we say that  $\{f_i : i \in I\}$  and  $\{g_i : i \in I\}$  are  
 548 *equivalent* if and only if the map  $f_i \mapsto g_i$  is extended to a homeomorphism  
 549 from  $\overline{\{f_i : i \in I\}}$  to  $\overline{\{g_i : i \in I\}}$ .
- 550 (2) If  $\{f_t : t \in 2^{<\mathbb{N}}\}$  is a pointwise bounded family, we say that  $\{f_t : t \in 2^{<\mathbb{N}}\}$   
 551 is *minimal* if and only if for every dyadic subtree  $\{s_t : t \in 2^{<\mathbb{N}}\}$  of  $2^{<\mathbb{N}}$ ,  
 552  $\{f_{s_t} : t \in 2^{<\mathbb{N}}\}$  is equivalent to  $\{f_t : t \in 2^{<\mathbb{N}}\}$ .

553 One of the main results in [ADK08] is that, up to equivalence, there are seven  
 554 minimal families of Rosenthal compacta and that for every relatively compact  $\{f_t :$   
 555  $t \in 2^{<\mathbb{N}}\} \subseteq B_1(X)$  there is a dyadic subtree  $\{s_t : t \in 2^{<\mathbb{N}}\}$  such that  $\{f_{s_t} : t \in 2^{<\mathbb{N}}\}$   
 556 is equivalent to one of the minimal families. We shall describe the seven minimal  
 557 families next. We follow the same notation as in [ADK08]. For any node  $t \in 2^{<\mathbb{N}}$ ,  
 558 let us denote by  $t \frown 0^\infty$  ( $t \frown 1^\infty$ ) the infinite binary sequence starting with  $t$  and  
 559 continuing with all 0's (respectively, all 1's). Fix a regular dyadic subtree  $R = \{s_t :$   
 560  $t \in 2^{<\mathbb{N}}\}$  of  $2^{<\mathbb{N}}$  (i.e., a dyadic subtree such that every level of  $R$  is contained  
 561 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  
 562  $s \frown 1^\infty \neq s' \frown 1^\infty$ . Given  $t \in 2^{<\mathbb{N}}$ , let  $v_t$  be the characteristic function of the set  
 563  $\{x \in 2^{\mathbb{N}} : x \text{ extends } t\}$ . Let  $<$  be the lexicographic order in  $2^{\mathbb{N}}$ . Given  $a \in 2^{\mathbb{N}}$ ,  
 564 let  $f_a^+ : 2^{\mathbb{N}} \rightarrow \{0, 1\}$  be the characteristic function of  $\{x \in 2^{\mathbb{N}} : a \leq x\}$  and let  
 565  $f_a^- : 2^{\mathbb{N}} \rightarrow \{0, 1\}$  be the characteristic function of  $\{x \in 2^{\mathbb{N}} : a < x\}$ . Given two  
 566 maps  $f, g : 2^{\mathbb{N}} \rightarrow \mathbb{R}$  we denote by  $(f, g) : 2^{\mathbb{N}} \sqcup 2^{\mathbb{N}} \rightarrow \mathbb{R}$  the function which is  $f$  on  
 567 the first copy of  $2^{\mathbb{N}}$  and  $g$  on the second copy of  $2^{\mathbb{N}}$ .

- 568 (1)  $D_1 = \{\frac{1}{|t|+1} v_t : t \in 2^{<\mathbb{N}}\}$ . This is discrete in  $\overline{D_1} = A(2^{\mathbb{N}})$ .
- 569 (2)  $D_2 = \{s_t \frown 0^\infty : t \in 2^{<\mathbb{N}}\}$ . This is discrete in  $\overline{D_2} = 2^{\leq \mathbb{N}}$ .
- 570 (3)  $D_3 = \{f_{s_t \frown 0^\infty}^+ : t \in 2^{<\mathbb{N}}\}$ . This is discrete in  $\overline{D_3} = S(2^{\mathbb{N}})$ .
- 571 (4)  $D_4 = \{f_{s_t \frown 1^\infty}^- : t \in 2^{<\mathbb{N}}\}$ . This is discrete in  $\overline{D_4} = S(2^{\mathbb{N}})$ .
- 572 (5)  $D_5 = \{v_t : t \in 2^{<\mathbb{N}}\}$ . This is discrete in  $\overline{D_5} = \hat{A}(2^{\mathbb{N}})$ .
- 573 (6)  $D_6 = \{(v_{s_t}, s_t \frown 0^\infty) : t \in 2^{<\mathbb{N}}\}$ . This is discrete in  $\overline{D_6} = \hat{D}(2^{\mathbb{N}})$ .
- 574 (7)  $D_7 = \{(v_{s_t}, x_{s_t \frown 0^\infty}^+) : t \in 2^{<\mathbb{N}}\}$ . 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  $i = 1, 2, \dots, 7$  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.*

#### 4. MEASURE-THEORETIC VERSIONS OF NIP AND ESSENTIAL COMPUTABILITY OF DEEP COMPUTATIONS

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 1.12 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 larger class.

**4.1. A measure-theoretic version of NIP.** Recall that the *raison d'être* of the class of Baire-1 functions is to have a class that contains the continuous functions but is closed under pointwise limits, and that (Fact 1.2) for perfectly normal  $X$ , a function  $f$  is in  $B_1(X, Y)$  if and only if  $f^{-1}[U]$  is an  $F_\sigma$  subset of  $X$  for every open  $U \subseteq Y$ . This motivates the following definition:

**Definition 4.1.** Given a Hausdorff space  $X$  and a measurable space  $(Y, \Sigma)$ , we say that  $f : X \rightarrow Y$  is *universally measurable* (with respect to  $\Sigma$ ) if  $f^{-1}(E)$  is Borel for every  $E \in \Sigma$ , i.e.,  $f^{-1}(E)$  is  $\mu$ -measurable for every Radon measure  $\mu$  on  $X$ . When  $Y = \mathbb{R}$  we will always take  $\Sigma = \mathcal{B}(\mathbb{R})$ , the Borel  $\sigma$ -algebra of  $\mathbb{R}$ .

*Remark 4.2.* A function  $f : X \rightarrow \mathbb{R}$  is universally measurable if and only if  $f^{-1}(U)$  is  $\mu$ -measurable for every Radon probability measure  $\mu$  on  $X$  and every open set  $U \subseteq \mathbb{R}$ .

Intuitively, a function is universally measurable if it is “measurable no matter which reasonable way you try to measure things on its domain”. The concept of universal measurability emerged from work of Kallianpur and Sazonov, in the late 1950’s and 1960s, with later developments by Blackwell, Darst, and others, building on earlier ideas of Gnedenko and Kolmogorov from the 1950s. See [Pap02, Chapters 1 and 2].

**Notation 4.3.** 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  $\sigma$ -algebras one can consider in the product space  $\mathbb{R}^{\mathcal{P}}$ : the Borel  $\sigma$ -algebra, i.e., the  $\sigma$ -algebra generated by open sets in  $\mathbb{R}^{\mathcal{P}}$ , and the cylinder  $\sigma$ -algebra, i.e., the  $\sigma$ -algebra generated by the sub-basic open sets in  $\mathbb{R}^{\mathcal{P}}$ . Note that when  $\mathcal{P}$  is countable, both  $\sigma$ -algebras coincide but in general the cylinder  $\sigma$ -algebra is strictly smaller. We will use the cylinder  $\sigma$ -algebra to define universally measurable maps  $f : \mathbb{R}^{\mathcal{P}} \rightarrow \mathbb{R}^{\mathcal{P}}$ . The reason for this choice is the following characterization:

**Lemma 4.4.** *Let  $X$  be a Hausdorff space and  $Y = \prod_{i \in I} Y_i$  be any product of measurable spaces  $(Y_i, \Sigma_i)$  for  $i \in I$ . Let  $\Sigma_Y$  be the cylinder  $\sigma$ -algebra generated by the measurable spaces  $(Y_i, \Sigma_i)$ . Let  $f : X \rightarrow Y$ . The following are equivalent:*

- (i)  $f : X \rightarrow Y$  is universally measurable (with respect to  $\Sigma_Y$ ).
- (ii)  $\pi_i \circ f : X \rightarrow Y_i$  is universally measurable (with respect to  $\Sigma_i$ ) for all  $i \in I$ .



619 *Proof.* (i) $\Rightarrow$ (ii) is clear since the projection maps  $\pi_i$  are measurable and the com-  
 620 position of measurable functions is measurable. To prove (ii) $\Rightarrow$ (i), suppose that  
 621  $C = \prod_{i \in I} C_i$  is a measurable cylinder and let  $J$  be the finite set of  $i \in I$  such that  
 622  $C_i \neq Y_i$ . 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  
 623 measurable set by assumption.  $\square$

624 The preceding lemma says that a transition map is universally measurable if and  
 625 only if it is universally measurable on all its features. In other words, we can check  
 626 measurability of a transition just by checking measurability feature by feature. We  
 627 will denote by  $M_r(X, \mathbb{R}^{\mathcal{P}})$  the collection of all universally measurable functions  
 628  $f : X \rightarrow \mathbb{R}^{\mathcal{P}}$  (with respect to the cylinder  $\sigma$ -algebra), endowed with the topology  
 629 of pointwise convergence.

630 We will need the following result about NIP and universally measurable func-  
 631 tions:

632 **Theorem 4.5** (Bourgain-Fremlin-Talagrand, Theorem 2F in [BFT78]). *Let  $X$  be a*  
 633 *Hausdorff space and  $A \subseteq C(X)$  be pointwise bounded. The following are equivalent:*

- 634 (i)  $\overline{A} \subseteq M_r(X)$ .
- 635 (ii) For every compact  $K \subseteq X$ ,  $A|_K$  satisfies the NIP.
- 636 (iii) For every Radon measure  $\mu$  on  $X$ ,  $A$  is relatively countably compact in  
 637  $\mathcal{M}^0(X, \mu)$ , i.e., every countable subset of  $A$  has an accumulation point in  
 638  $\mathcal{M}^0(X, \mu)$ .

639 **4.2. Essential computability of deep computations.** We now wish to define  
 640 the concept of a deep computation being computable except a set of arbitrarily  
 641 small measure “no matter which reasonable way you try to measure things on its  
 642 domain” (see the remarks following definition ). This is the concept of *universal*  
 643 *measurability* defined below (Definition ). To motivate the definition, we need to  
 644 recall two facts:

- 645 (1) Littlewood’s second principle states that every Lebesgue measurable func-  
 646 tion is “nearly continuous”. The formal version of this, which is Luzin’s  
 647 theorem, states that if  $(X, \Sigma, \mu)$  a Radon measure space and  $Y$  be a second-  
 648 countable topological space (e.g.,  $Y = \mathbb{R}^{\mathcal{P}}$  with  $\mathcal{P}$  countable ) equipped with  
 649 a Borel algebra, then any given  $f : X \rightarrow Y$  is measurable if and only if for  
 650 every  $E \in \Sigma$  and every  $\varepsilon > 0$  there exists a closed  $F \subseteq E$  such that the  
 651 restriction  $f|_F$  is continuous.
- 652 (2) Computability of deep computations can be characterized in terms of con-  
 653 tinuous extendibility of computations. This is at the core of [ADIW24].

654 These facts motivate the following definition:

655 **Definition 4.6.** Let  $(L, \mathcal{P}, \Gamma)$  be a CCS. We say that a transition  $f : L \rightarrow L$   
 656 is *universally essentially computable* if and only if there exists  $\tilde{f} : \mathcal{L}_{\text{sh}} \rightarrow \mathcal{L}_{\text{sh}}$   
 657 extending  $f$  such that for every sizer  $r_{\bullet}$  there is a sizer  $s_{\bullet}$  such that the restriction  
 658  $\tilde{f}|_{\mathcal{L}[r_{\bullet}]} : \mathcal{L}[r_{\bullet}] \rightarrow \mathcal{L}[s_{\bullet}]$  is universally measurable, i.e.,  $\pi_P \circ \tilde{f}|_{\mathcal{L}[r_{\bullet}]} : \mathcal{L}[r_{\bullet}] \rightarrow [-s_P, s_P]$   
 659 is  $\mu$ -measurable for every Radon probability measure  $\mu$  on  $\mathcal{L}[r_{\bullet}]$ .

660 **4.3. Bourgain-Fremlin-Talagrand, NIP, and essential computability of**  
 661 **deep computations.** Theorem 4.5 immediately yields the following.

662 **Theorem 4.7.** *Let  $(L, \mathcal{P}, \Gamma)$  be a CCS satisfying the Extendability Axiom. Let  $R$  be*  
 663 *an exhaustive collection of sizers. Let  $\Delta \subseteq \Gamma$  be  $R$ -confined. If  $\pi_P \circ \Delta|_{L[r_{\bullet}]}$  satisfies*

664 the NIP for all  $P \in \mathcal{P}$  and all  $r_\bullet \in R$ , then every deep computation is universally  
 665 essentially computable.

666 *Proof.* By the Extendability Axiom, Theorem 4.5 and lemma 1.13 we have that  
 667  $\pi_P \circ \tilde{\Delta}|_{\mathcal{L}[r_\bullet]} \subseteq M_r(\mathcal{L}[r_\bullet])$  for all  $r_\bullet \in R$  and  $P \in \mathcal{P}$ . Let  $f \in \bar{\Delta}$  be a deep  
 668 computation. Write  $f = \mathcal{U} \lim_i \gamma_i$  as an ultralimit of computations in  $\Delta$ . De-  
 669 fine  $\tilde{f} := \mathcal{U} \lim_i \tilde{\gamma}_i$ . 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  
 670  $i$ , so  $\pi_P \circ \tilde{f}|_{\mathcal{L}[r_\bullet]} \in \pi_P \circ \tilde{\Delta}|_{\mathcal{L}[r_\bullet]} \subseteq M_r(\mathcal{L}[r_\bullet])$ .  $\square$

671 **Question 4.8.** Under the same assumptions of the preceding theorem, suppose  
 672 that every deep computation of  $\Delta$  is universally essentially computable. Must  
 673  $\pi_P \circ \Delta|_{\mathcal{L}[r_\bullet]}$  have the NIP for all  $P \in \mathcal{P}$  and all  $r_\bullet \in R$ ?

674 **4.4. Talagrand stability, Fremlin's dichotomy, NIP, and essential com-**  
 675 **putability of deep computations.** There is another notion closely related to  
 676 NIP, introduced by Talagrand in [Tal84] while studying Pettis integration. Suppose  
 677 that  $X$  is a compact Hausdorff space and  $A \subseteq \mathbb{R}^X$ . Let  $\mu$  be a Radon probability  
 678 measure on  $X$ . Given a  $\mu$ -measurable set  $E \subseteq X$ , a positive integer  $k$  and real  
 679 numbers  $a < b$ , we write:

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

680 We say that  $A$  is *Talagrand  $\mu$ -stable* if and only if for every  $\mu$ -measurable set  
 681  $E \subseteq X$  of positive measure and for every  $a < b$  there is  $k \geq 1$  such that

$$(\mu^{2k})^*(D_k(A, E, a, b)) < (\mu(E))^{2k},$$

682 where  $\mu^*$  denotes the outer measure (we work with outer since the sets  $D_k(A, E, a, b)$   
 683 need not be  $\mu$ -measurable). This is certainly the case when  $A$  is a countable set of  
 684 continuous (or  $\mu$ -measurable) functions.

685 **Notation 4.9.** For a measure  $\mu$  on a set  $X$ , the set of all  $\mu$ -measurable functions  
 686 will be denoted by  $\mathcal{M}^0(X, \mu)$ .

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

690 **Lemma 4.10.** *If  $A$  is Talagrand  $\mu$ -stable, then  $\bar{A}$  is also Talagrand  $\mu$ -stable and*  
 691  $\bar{A} \subseteq \mathcal{M}^0(X, \mu)$ .

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

We say that  $A$  is *universally Talagrand stable* if  $A$  is Talagrand  $\mu$ -stable for every Radon probability measure  $\mu$  on  $X$ . An argument similar to the proof of 4.5, yields the following:

**Theorem 4.11.** *Let  $(L, \mathcal{P}, \Gamma)$  be a CCS satisfying the Extendability Axiom. If  $\pi_P \circ \Delta|_{L[r_\bullet]}$  is universally Talagrand stable for all  $P \in \mathcal{P}$  and all sizes  $r_\bullet$ , then every deep computation is universally essentially computable.*

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

**Lemma 4.12** (Fremlin's Dichotomy, 463K in [Fre03]). *If  $(X, \Sigma, \mu)$  is a perfect  $\sigma$ -finite measure space (in particular, for  $X$  compact and  $\mu$  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  $\mu$ -almost everywhere, or
- (ii)  $\{f_n : n \in \mathbb{N}\}$  has a subsequence with no  $\mu$ -measurable accumulation point in  $\mathbb{R}^X$ .

The preceding lemma can be considered as a measure-theoretic version of Rosenthal's Dichotomy. Combining this dichotomy with the Theorem 4.5 we get the following result:

**Theorem 4.13.** *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  $K \subseteq X$ ,  $A|_K$  satisfies the NIP.
- (iii) For every Radon measure  $\mu$  on  $X$ ,  $A$  is relatively countably compact in  $\mathcal{M}^0(X, \mu)$ , i.e., every countable subset of  $A$  has an accumulation point in  $\mathcal{M}^0(X, \mu)$ .
- (iv) For every Radon measure  $\mu$  on  $X$  and every sequence  $\{f_n : n \in \mathbb{N}\} \subseteq A$ , there is a subsequence that converges  $\mu$ -almost everywhere.

*Proof.* Notice that the equivalence (i)-(iii) is Theorem 4.5. Notice that the equivalence of (iii) and (iv) is Fremlin's Dichotomy (Theorem 4.12).  $\square$

Finally, it is natural to ask what the connection is between Talagrand stability and NIP.

**Proposition 4.14.** *Let  $X$  be a compact Hausdorff space and  $A \subseteq C(X)$  be pointwise bounded. If  $A$  is universally Talagrand stable, then  $A$  satisfies the NIP.*

*Proof.* By Theorem 4.5, it suffices to show that  $A$  is relatively countably compact in  $\mathcal{M}^0(X, \mu)$  for all Radon probability measure  $\mu$  on  $X$ . Since  $A$  is Talagrand  $\mu$ -stable for any such  $\mu$ , we have  $\overline{A} \subseteq \mathcal{M}^0(X, \mu)$ . In particular,  $A$  is relatively countably compact in  $\mathcal{M}^0(X, \mu)$ .  $\square$

**Question 4.15.** Is the converse true?

The following two results suggest that the precise connection between Talagrand stability and NIP may be sensitive to set-theoretic axioms (even assuming countability of  $A$ ).

- 743 **Theorem 4.16** (Talagrand, Theorem 9-3-1(a) in [Tal84]). *Let  $X$  be a compact*  
 744 *Hausdorff space and  $A \subseteq M_r(X)$  be countable and pointwise bounded. Assume that*  
 745  *$[0, 1]$  is not the union of  $< \mathfrak{c}$  closed measure zero sets. If  $A$  satisfies the NIP, then*  
 746  *$A$  is universally Talagrand stable.*
- 747 **Theorem 4.17** (Fremlin, Shelah, [FS93]). *It is consistent that there exists a count-*  
 748 *able pointwise bounded set of Lebesgue measurable functions with the NIP which is*  
 749 *not Talagrand stable with respect to Lebesgue measure.*

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