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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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113 1. GENERAL TOPOLOGICAL PRELIMINARIES: FROM CONTINUITY TO BAIRE 114 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_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

130 inherited from the reals not complete, but it is Polish since that is homeomorphic
 131 to the real line. Being Polish is a topological property.

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

136 **Fact 1.1.** *A subset A of a Polish space X is itself Polish in the subspace topology*
 137 *if and only if it is a G_δ set. In particular, closed subsets and open subsets of Polish*
 138 *spaces are also Polish spaces.*

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

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

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

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

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

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

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

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

170 A subset L of a topological space X is *relatively compact* in X if the closure
 171 of L in X is compact. Relatively compact subsets of $B_1(X)$ (for X Polish) have
 172 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 $\beta\mathbb{N}$.*

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

223 The genesis of Theorem 1.4 was Rosenthal’s ℓ_1 theorem, which states that the
 224 only reason why Banach space can fail to have an isomorphic copy of ℓ_1 (the space
 225 of absolutely summable sequences) is the presence of a bounded sequence with no
 226 weakly Cauchy subsequence. The theorem is famous for connecting diverse areas
 227 of mathematics, namely, Banach space geometry, Ramsey theory, set theory, and
 228 topology of function spaces.

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

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

- 236 (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*

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

237 **Definition 1.6.** We shall say that a set $A \subseteq \mathbb{R}^X$ satisfies the *Independence Prop-*
 238 *erty*, or IP for short, if it satisfies the following condition: There exists every
 239 $\{f_n\}_{n \in \mathbb{N}} \subseteq A$ and $a < b$ such that for every pair of disjoint sets $E, F \subseteq \mathbb{N}$, we
 240 have

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

241 If A satisfies the negation of this condition, we will say that A *satisfies NIP*, or
 242 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

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

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

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

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

249 The Independence Property was first isolated by Saharon Shelah in model theory
 250 as a dividing line between theories whose models are “tame” (corresponding to
 251 NIP) theories of models are “wild” (corresponding to IP). See [She71, Definition
 252 4.1], [She90]. We will discuss this dividing line in more detail in the next section.

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

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

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

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

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

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

In machine learning: Readers familiar with statistical learning may recognize the Sauer-Shelah lemma as the dichotomy discovered and proved slightly earlier (1971) by Vapnik and Chervonenkis [VC71, VC74] to address the problem of uniform convergence in statistics. The least integer N given by the preceding paragraph, when it exists, is called the *VC-dimension* of \mathcal{F} . This is a core concept in machine learning. If such an 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_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 $f : X \rightarrow \mathbb{R}^{\mathcal{P}}$ 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_σ for every $P \in \mathcal{P}$. Given that \mathcal{P} is a discrete countable space, we observe that

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

is an F_σ 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,

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

330 which is F_σ . □

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

334 **Theorem 1.12.** *Assume that \mathcal{P} is countable, X is a Polish space, and $A \subseteq$
335 $C_p(X, \mathbb{R}^\mathbb{P})$ is such that $\pi_P \circ A$ is pointwise bounded for all $P \in \mathcal{P}$. The follow-
336 ing are equivalent for every compact $K \subseteq X$:*

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

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

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

340 (2) \Rightarrow (1) Fix $f \in \overline{A|_K}$. By lemma 1.10 it suffices to show that $\pi_P \circ f \in B_1(K)$
341 for all $P \in \mathcal{P}$. By (2), $\pi_P \circ A|_K$ satisfies the NIP. Hence, by Theorem 1.8 we have
342 $\overline{\pi_P \circ A|_K} \subseteq B_1(K)$. But then $\pi_P \circ f \in \overline{\pi_P \circ A|_K} \subseteq B_1(K)$. □

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

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

- 348 (i) A_L satisfies the NIP.
- 349 (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 $E, F \subseteq \mathbb{N}$:

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

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

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

By definition of closure:

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

350 This contradicts (i). □

351 2. COMPOSITIONAL COMPUTATION STRUCTURES.

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

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

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

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

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

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

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

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

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

380 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}_{sh} , as
381 the union of all type-shards.

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

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

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

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 ε -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 ε -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 φ 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}, Γ) 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 γ .

By the preceding remarks, the Extendability Axiom says that the elements of the semigroup Γ are definable. For the rest of the paper, fix for each $\gamma \in \Gamma$ a free extension $\tilde{\gamma}$ of γ . 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 ∞). 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

428 root of p , $\gamma_p : \hat{\mathbb{C}} \rightarrow \hat{\mathbb{C}}$. The explicit inner workings of γ_p are irrelevant for this
 429 example, except for the fact that it is a continuous mapping. It follows that
 430 $(S^2, \{x, y, z\}, \{\gamma_p^k : k \in \mathbb{N}\})$ is a CCS. The idea is that repeated applications of
 431 $\gamma_p(s), \gamma_p \circ \gamma_p(s), \gamma_p \circ \gamma_p \circ \gamma_p(s), \dots$ would approximate a root of p provided s was a
 432 good enough initial guess.

433

3. CLASSIFYING DEEP COMPUTATIONS

434 **3.1. NIP, Rosenthal compacta, and deep computations.** Under what condi-
 435 tions are deep computations Baire class 1, and thus well-behaved according to our
 436 framework, on type-shards? The following theorem says that, under the assump-
 437 tion that \mathcal{P} is countable, the space of deep computations is a Rosenthal compactum
 438 (when restricted to shards) if and only if the set of computations satisfies the NIP
 439 feature by feature. Hence, we can import the theory of Rosenthal compacta into
 440 this framework of deep computations.

441 **Theorem 3.1.** *Let (L, \mathcal{P}, Γ) be a compositional computational structure (Defini-*
 442 *tion 2.3) satisfying the Extendability Axiom (Definition 2.4) with \mathcal{P} countable. Let*
 443 *R be an exhaustive collection of sizers. Let $\Delta \subseteq \Gamma$ be R -confined. The following*
 444 *are equivalent.*

- 445 (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) $\pi_P \circ \Delta|_{\mathcal{L}[r_\bullet]}$ 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

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

446 Moreover, if any (hence all) of the preceding conditions hold, then every deep
 447 computation $f \in \overline{\tilde{\Delta}}$ can be extended to a Baire-1 function on shards, i.e., there is
 448 $\tilde{f} : \mathcal{L}_{sh} \rightarrow \mathcal{L}_{sh}$ 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
 449 each shard every deep computation is the pointwise limit of a countable sequence of
 450 computations.

451 *Proof.* Since \mathcal{P} is countable, $\mathcal{L}[r_\bullet] \subseteq \mathbb{R}^{\mathcal{P}}$ is Polish. Also, the Extendability Axiom
 452 implies that $\pi_P \circ \tilde{\Delta}|_{\mathcal{L}[r_\bullet]}$ is a pointwise bounded set of continuous functions for all
 453 $P \in \mathcal{P}$. Hence, Theorem 1.12 and Lemma 1.13 prove the equivalence of (1) and (2).
 454 If (1) holds and $f \in \overline{\tilde{\Delta}}$, then write $f = \mathcal{U}\lim_i \gamma_i$ as an ultralimit. Define $\tilde{f} := \mathcal{U}\lim_i \tilde{\gamma}_i$.
 455 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
 456 deep computation is a pointwise limit of a countable sequence of computations
 457 follows from the fact that for a Polish space X every compact subset of $B_1(X)$ is
 458 Fréchet-Urysohn (that is, a space where topological closures coincide with sequential
 459 closures, see Theorem 3F in [BFT78] or Theorem 4.1 in [Deb13]). \square

460 **3.2. The Todorćević trichotomy and levels of PAC learnability.** Given a
 461 countable set Δ of computations satisfying the NIP on features and shards (con-
 462 dition (2) of Theorem 3.1) we have that $\overline{\tilde{\Delta}|_{\mathcal{L}[r_\bullet]}}$ (for a fixed sizer r_\bullet) is a separable
 463 Rosenthal compactum (see Definition 1.9). Todorćević proved a trichotomy for
 464 Rosenthal compacta [Tod99], and later Argyros, Dodos, Kanellopoulos [ADK08]
 465 proved an heptachotomy that refined Todorćević's classification. In this section,

inspired by the work of Glasner and Megrelishvili [GM22], we study ways in which this classification allows us obtain different levels of PAC-learnability and 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 of [Deb13]). This suggests the following definition:

Definition 3.2. Let (L, \mathcal{P}, Γ) be a CCS satisfying the Extendability 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], Todorćević isolates three 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:

Examples 3.3.

- (1) *Alexandroff compactification of a discrete space of size continuum.* For each $a \in 2^{\mathbb{N}}$ consider the map $\delta_a : 2^{\mathbb{N}} \rightarrow \mathbb{R}$ 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 $v_s : 2^{\mathbb{N}} \rightarrow \mathbb{R}$ be given by $v_s(x) = 1$ if x extends s and $v_s(x) = 0$ otherwise. Let $\hat{A}(2^{\mathbb{N}})$ be the pointwise closure of $\{v_s : s \in 2^{<\mathbb{N}}\}$, i.e., $\hat{A}(2^{\mathbb{N}}) = A(2^{\mathbb{N}}) \cup \{v_s : s \in 2^{<\mathbb{N}}\}$. 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 $f_a^- : 2^{\mathbb{N}} \rightarrow \mathbb{R}$ be given by $f_a^-(x) = 1$ if $x < a$ and $f_a^-(x) = 0$ otherwise. Let $f_a^+ : 2^{\mathbb{N}} \rightarrow \mathbb{R}$ be given by $f_a^+(x) = 1$ if $x \leq a$ 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 $g_a^0, g_a^1 : X \rightarrow \mathbb{R}$

as follows:

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

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

507 Let $D(K) = \{g_a^0 : a \in K\} \cup \{g_a^1 : a \in K\}$. Notice that $D(K)$ is a first
508 countable Rosenthal compactum. It is not separable if K is uncountable.
509 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

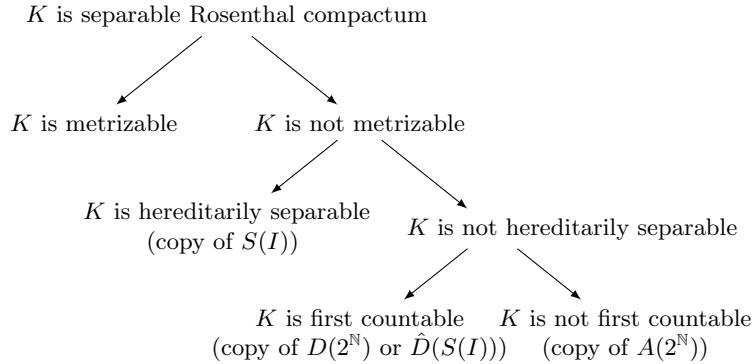
$$h_t(x) = \begin{cases} 0, & x < a_t \\ 1/2, & a_t \leq x \leq b_t \\ 1, & b_t < x \end{cases}$$

510 Let $\hat{D}(S(2^{\mathbb{N}}))$ be the pointwise closure of the set $\{h_t : t \in 2^{<\mathbb{N}}\}$. Hence,
511 $\hat{D}(S(2^{\mathbb{N}}))$ is a separable first countable Rosenthal compactum which is not
512 hereditarily separable. In fact, it contains an uncountable discrete subspace
513 (see Theorem 5 in [Tod99]).

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

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

520 We thus have the following classification:



521

522 The definitions provided here for NIP_i ($i = 1, 2, 3$) are topological. This raises
523 the following question:

524 **Question 3.5.** Is there a non-topological characterization for NIP_i , $i = 1, 2, 3$?

525 **3.3. The Argyros-Dodos-Kanellopoulos heptachotomy, and approxima-**
 526 **bility of deep computation by minimal classes.** In the three separable three
 527 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-
 528 sets are indexed by the binary tree $2^{<\mathbb{N}}$. This choice of index is useful for two
 529 reasons:

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

540 **Definition 3.6.** Let X be a Polish space.

- 541 (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
 542 pointwise families by I , we say that $\{f_i : i \in I\}$ and $\{g_i : i \in I\}$ are
 543 *equivalent* if and only if the map $f_i \mapsto g_i$ is extended to a homeomorphism
 544 from $\overline{\{f_i : i \in I\}}$ to $\overline{\{g_i : i \in I\}}$.
- 545 (2) If $\{f_t : t \in 2^{<\mathbb{N}}\}$ is a pointwise bounded family, we say that $\{f_t : t \in 2^{<\mathbb{N}}\}$
 546 is *minimal* if and only if for every dyadic subtree $\{s_t : t \in 2^{<\mathbb{N}}\}$ of $2^{<\mathbb{N}}$,
 547 $\{f_{s_t} : t \in 2^{<\mathbb{N}}\}$ is equivalent to $\{f_t : t \in 2^{<\mathbb{N}}\}$.

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

- 563 (1) $D_1 = \{\frac{1}{|t|+1} v_t : t \in 2^{<\mathbb{N}}\}$. This is discrete in $\overline{D_1} = A(2^{\mathbb{N}})$.
- 564 (2) $D_2 = \{s_t \frown 0^\infty : t \in 2^{<\mathbb{N}}\}$. This is discrete in $\overline{D_2} = 2^{\leq \mathbb{N}}$.
- 565 (3) $D_3 = \{f_{s_t \frown 0^\infty}^+ : t \in 2^{<\mathbb{N}}\}$. This is a discrete in $\overline{D_3} = S(2^{\mathbb{N}})$.
- 566 (4) $D_4 = \{f_{s_t \frown 1^\infty}^- : t \in 2^{<\mathbb{N}}\}$. This is discrete in $\overline{D_4} = S(2^{\mathbb{N}})$.
- 567 (5) $D_5 = \{v_t : t \in 2^{<\mathbb{N}}\}$. This is discrete in $\overline{D_5} = \hat{A}(2^{\mathbb{N}})$.
- 568 (6) $D_6 = \{(v_{s_t}, s_t \frown 0^\infty) : t \in 2^{<\mathbb{N}}\}$. This is discrete in $\overline{D_6} = \hat{D}(2^{\mathbb{N}})$.
- 569 (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.*

3.4. Bourgain-Fremlin-Talagrand, 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. 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_σ subset of X for every open $U \subseteq Y$. This motivates the following definition:

Definition 3.8. Given a Hausdorff space X and a measurable space (Y, Σ) , we say that $f : X \rightarrow Y$ is *universally measurable* (with respect to Σ) if $f^{-1}(E)$ is Borel 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 this case, a function $f : X \rightarrow \mathbb{R}$ 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 $U \subseteq \mathbb{R}$.

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].

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 the sub-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 $f : \mathbb{R}^{\mathcal{P}} \rightarrow \mathbb{R}^{\mathcal{P}}$. The reason for this choice is the following characterization:

Lemma 3.9. *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 $f : X \rightarrow Y$. The following are equivalent:*

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

Proof. (i) \Rightarrow (ii) is clear since the projection maps π_i are measurable and the composition of measurable functions is measurable. To prove (ii) \Rightarrow (i), suppose that $C = \prod_{i \in I} C_i$ is a measurable cylinder and let J be the finite set of $i \in I$ such that $C_i \neq Y_i$. 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 measurable set by assumption. \square

616 The preceding lemma says that a transition map is universally measurable if and
 617 only if it is universally measurable on all its features. In other words, we can check
 618 measurability of a transition just by checking measurability feature by feature. We
 619 will denote by $M_r(X, \mathbb{R}^{\mathcal{P}})$ the collection of all universally measurable functions
 620 $f : X \rightarrow \mathbb{R}^{\mathcal{P}}$ (with respect to the cylinder σ -algebra), endowed with the topology
 621 of pointwise convergence.

622 We now wish to define the concept of a deep computation being computable
 623 except a set of arbitrarily small measure “no matter which reasonable way you try
 624 to measure things on its domain” (see the remarks following definition). This is
 625 definition below. To motivate the definition, we need to recall two facts:

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

635 These facts motivate the following definition:

636 **Definition 3.10.** Let (L, \mathcal{P}, Γ) be a CCS. We say that a transition $f : L \rightarrow L$
 637 is *universally essentially computable* if and only if there exists $\tilde{f} : \mathcal{L}_{\text{sh}} \rightarrow \mathcal{L}_{\text{sh}}$
 638 extending f such that for every sizer r_{\bullet} there is a sizer s_{\bullet} such that the restriction
 639 $\tilde{f}|_{\mathcal{L}[r_{\bullet}]} : \mathcal{L}[r_{\bullet}] \rightarrow \mathcal{L}[s_{\bullet}]$ is universally measurable, i.e., $\pi_P \circ \tilde{f}|_{\mathcal{L}[r_{\bullet}]} : \mathcal{L}[r_{\bullet}] \rightarrow [-s_P, s_P]$
 640 is μ -measurable for every Radon probability measure μ on $\mathcal{L}[r_{\bullet}]$.

641 For a measure μ on $\text{a}X$, the set of all μ -measurable functions will be denoted by
 642 $\mathcal{M}^0(X, \mu)$.

643 We will need the following result about NIP and universally measurable func-
 644 tions:

645 **Theorem 3.11** (Bourgain-Fremlin-Ta set lagrand, Theorem 2F in [BFT78]). *Let*
 646 *X be a Hausdorff space and $A \subseteq C(X)$ be pointwise bounded. The following are*
 647 *equivalent:*

- 648 (i) $\overline{A} \subseteq M_r(X)$.
- 649 (ii) For every compact $K \subseteq X$, $A|_K$ satisfies the NIP.
- 650 (iii) For every Radon measure μ on X , A is relatively countably compact in
 651 $\mathcal{M}^0(X, \mu)$, i.e., every countable subset of A has an accumulation point in
 652 $\mathcal{M}^0(X, \mu)$.

653 Theorem 1.8 immediately yields the following.

654 **Theorem 3.12.** *Let (L, \mathcal{P}, Γ) be a CCS satisfying the Extendability Axiom. Let*
 655 *R be an exhaustive collection of sizers. Let $\Delta \subseteq \Gamma$ be R -confined. If $\pi_P \circ \Delta|_{\mathcal{L}[r_{\bullet}]}$*
 656 *satisfies the NIP for all $P \in \mathcal{P}$ and all $r_{\bullet} \in R$, then every deep computation is*
 657 *universally essentially computable.*

658 *Proof.* By the Extendability Axiom, Theorem 1.8 and lemma 1.13 we have that
 659 $\pi_P \circ \tilde{\Delta}|_{\mathcal{L}[r_{\bullet}]} \subseteq M_r(\mathcal{L}[r_{\bullet}])$ for all $r_{\bullet} \in R$ and $P \in \mathcal{P}$. Let $f \in \overline{\Delta}$ be a deep

computation. Write $f = \mathcal{U} \lim_i \gamma_i$ as an ultralimit of computations in Δ . Define $\tilde{f} := \mathcal{U} \lim_i \tilde{\gamma}_i$. 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 $\pi_P \circ f|_{\mathcal{L}[r_\bullet]} \in \overline{\pi_P \circ \tilde{\Delta}|_{\mathcal{L}[r_\bullet]}} \subseteq M_r(\mathcal{L}[r_\bullet])$. \square

Question 3.13. Under the same assumptions of the preceding theorem, suppose that every deep computation of Δ is universally essentially computable. Must $\pi_P \circ \Delta|_{\mathcal{L}[r_\bullet]}$ have the NIP for all $P \in \mathcal{P}$ and all $r_\bullet \in R$?

3.5. Talagrand stability, NIP, and essential computability of deep computations. 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:

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

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 $k \geq 1$ such that

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

where μ^* denotes the outer measure (we work with outer since the sets $D_k(A, E, a, b)$ need not be 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 a proof for the reader's convenience.

Lemma 3.14. *If A is Talagrand μ -stable, then \overline{A} is also Talagrand μ -stable and $\overline{A} \subseteq \mathcal{M}^0(X, \mu)$.*

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 $\overline{A} \subseteq \mathcal{M}^0(X, \mu)$. Suppose that there exists $f \in \overline{A}$ such that $f \notin \mathcal{M}^0(X, \mu)$. 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 $P = \{x \in E : f(x) \leq a\}$ and $Q = \{x \in E : f(x) \geq b\}$. Then, for any $k \geq 1$: $(P \times Q)^k \subseteq D_k(\{f\}, E, a, b)$ 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 . An argument similar to the proof of 3.11, yields the following:

Theorem 3.15. *Let (L, \mathcal{P}, Γ) be a CCS satisfying the Extendability Axiom. If $\pi_P \circ \Delta|_{\mathcal{L}[r_\bullet]}$ 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.

699 **Lemma 3.16** (Fremlin's Dichotomy, 463K in [Fre03]). *If (X, Σ, μ) is a perfect*
700 *σ -finite measure space (in particular, for X compact and μ a Radon probability*
701 *measure on X) and $\{f_n : n \in \mathbb{N}\}$ be a sequence of real-valued measurable functions*
702 *on X , then either*

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

706 The preceding lemma can be considered as a measure-theoretic version of Rosen-
707 thal's Dichotomy. Combining this dichotomy with the Theorem 3.11 we get the
708 following result:

709 **Theorem 3.17.** *Let X be a Hausdorff space and $A \subseteq C(X)$ be pointwise bounded.*
710 *The following are equivalent:*

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

718 *Proof.* Notice that the equivalence (i)-(iii) is Theorem 3.11. Notice that the equiv-
719 alence of (iii) and (iv) is Fremlin's Dichotomy (Theorem 3.16). \square

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

722 **Proposition 3.18.** *Let X be a compact Hausdorff space and $A \subseteq C(X)$ be point-*
723 *wise bounded. If A is universally Talagrand stable, then A satisfies the NIP.*

724 *Proof.* By Theorem 3.11, it suffices to show that A is relatively countably compact
725 in $\mathcal{M}^0(X, \mu)$ for all Radon probability measure μ on X . Since A is Talagrand
726 μ -stable for any such μ , we have $\overline{A} \subseteq \mathcal{M}^0(X, \mu)$. In particular, A is relatively
727 countably compact in $\mathcal{M}^0(X, \mu)$. \square

728 **Question 3.19.** Is the converse true?

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

732 **Theorem 3.20** (Talagrand, Theorem 9-3-1(a) in [Tal84]). *Let X be a compact*
733 *Hausdorff space and $A \subseteq M_r(X)$ be countable and pointwise bounded. Assume that*
734 *$[0, 1]$ is not the union of $< \mathfrak{c}$ closed measure zero sets. If A satisfies the NIP, then*
735 *A is universally Talagrand stable.*

736 **Theorem 3.21** (Fremlin, Shelah, [FS93]). *It is consistent that there exists a count-*
737 *able pointwise bounded set of Lebesgue measurable functions with the NIP which is*
738 *not Talagrand stable with respect to Lebesgue measure.*

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