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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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## 1. 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], etc). In this paper, we combine ideas of topology 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, real-valued functions that arise as the pointwise limit of a sequence of continuous are called *functions of the first Baire class*, or *Baire class 1* functions, or *Baire-1* for short; Baire class 1 form a step above simple continuity in the hierarchy of functions studied in real analysis (Baire class 0 functions being continuous functions). Intuitively, Baire-1 functions represent functions with “controlled” discontinuities, so they are crucial in topology and set theory.

We prove a new “tame vs wild” Ramsey-theoretic dichotomy for complexity of general deep computations by invoking a famous paper by Bourgain, Fremlin and Talagrand from the late 70s [BFT78], and a new trichotomy for the class of “tame” deep computations by invoking an equally celebrated result of 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 the fundamental “prototypes” of separable Rosenthal compacta, and proved that any non-metrizable separable Rosenthal compactum must contain a “canonical” embedding of one of these prototypes. They showed that if a separable Rosenthal compactum is not hereditarily separable, it must contain an uncountable discrete subspace of the size of the continuum.

We believe that the results presented in this paper show practitioners of computation, or topology, or descriptive set theory, or model theory, how classification invariants used in their field translate into classification invariants of other fields. However, in the interest of accessibility, we do not assume previous familiarity with

high-level topology or model theory, or computing. The only technical prerequisite of the paper is undergraduate-level topology. The necessary topological background beyond undergraduate topology is covered in section 2.

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

## 2. GENERAL TOPOLOGICAL PRELIMINARIES

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

Recall that a subset of a topological space is  $F_\sigma$  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 products of Polish spaces are Polish; this includes spaces like  $\mathbb{R}^{\mathbb{N}}$ , the space of sequences of real numbers.

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

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

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

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

A *Baire class 1* function between topological spaces is a function that can be expressed as the pointwise limit of a sequence of continuous functions. If  $X$  and  $Y$  are topological spaces, the Baire class 1 functions  $f : X \rightarrow Y$  endowed with the topology of pointwise convergence is denoted  $B_1(X, Y)$ . As above, in the special case  $Y = \mathbb{R}$  we denote  $B_1(X, Y)$  as  $B_1(X)$ . Clearly,  $C_p(X, Y) \subseteq B_1(X, Y)$ . The Baire

hierarchy of functions was introduced by French mathematician René-Louis Baire in his 1899 doctoral thesis, *Sur les fonctions de variables réelles*. His work moved away from the 19th-century preoccupation with "pathological" functions toward a constructive classification based on pointwise limits.

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

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

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

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

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

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

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

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

- (i)  $A$  is relatively compact in  $B_1(X)$ .
- (ii)  $A$  is relatively countably compact in  $B_1(X)$ , i.e., every countable subset of  $A$  has an accumulation point in  $B_1(X)$ .
- (iii)  $\overline{A} \subseteq B_1(X)$ , where  $\overline{A}$  denotes the closure in  $\mathbb{R}^X$ .

*Proof.* 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 2.2, there are countable  $D_0, D_1 \subseteq X$  with  $\overline{D_0} = \overline{D_1}$ , and  $a < b$  such that  $D_0 \subseteq f^{-1}(-\infty, a]$  and  $D_1 \subseteq f^{-1}[b, \infty)$ . We claim that there is a sequence  $\{f_n\}_{n \in \mathbb{N}} \subseteq A$  such that  $\lim_{n \rightarrow \infty} f_n(x) = f(x)$  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 2.2.

(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.  $\square$

**2.1. From Rosenthal's dichotomy to Shelah's NIP.** The fundamental idea that connects the rich theory here presented to real-valued computations is the concept of an *approximation*. In the reals, points of closure from 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 2.4** (Rosenthal's Dichotomy, 1974). *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.

As we go 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 2.5** (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 2.6.** We shall say that a set  $A \subseteq \mathbb{R}^X$  has 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 2.7.* Note that if  $X$  is compact and  $A \subseteq C_p(X)$ , then  $A$  has the NIP if and only if for every  $\{f_n\}_{n \in \mathbb{N}} \subseteq A$  and for every  $a < b$  there is  $I \subseteq \mathbb{N}$  such that

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

To summarize, the particular case of Theorem 2.8 when for  $X$  compact can be stated in the following way:

**Theorem 2.8.** *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.

The Independence Property was first isolated by Saharon Shelah in model theory as a dividing line between theories whose models are “tame” (corresponding to NIP) theories of models are “wild” (corresponding to IP). See [She71, Definition 4.1], [She90].

**2.2. A universal polynomial vs exponential dichotomy.** The particular case of the BSF Dichotomy (Theorem 2.8) 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].

Saharon 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. This number 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  $\kappa$  of such a theory is of polynomially or similar “slow” growth on  $\kappa$ . Theories with the Independence Property (called IP theories), in contrast, 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  $\kappa$ , the theory will have  $2^{2^\kappa}$ -many distinct types.

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 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  $A \subseteq S$  with  $|A| \geq N$ , one has

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

for every  $A \subseteq S$  such that  $|A| \geq N$  (yielding polynomial complexity). This answered a question of Erdős.

Readers familiar with statistical learning may recognize the Sauer-Shelah lemma as the dichotomy discovered and proved slightly (1971) earlier by Vapknis and Chervononkis [VC71, VC74] to address the problem of uniform convergence in statistics. The 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. The lemma provides upper bounds on the number of data points (sample size  $m$ ) needed to learn a concept class with VC dimension  $d$  by showing this number grows polynomially with  $m$  and  $d$  (namely,  $\sum_{i=0}^d \binom{m}{i} \approx O(m^d)$ ), not exponentially.

**2.3. The special case  $Y = \mathbb{R}^{\mathcal{P}}$  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 subsequent 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 2.9.** *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 2.10.** *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 2.9, 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

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

is an  $F_\sigma$  as well.

( $\Leftarrow$ ) By lemma 2.9 it suffices to show that  $\pi_P \circ f \in B_1(X)$  for all  $P \in \mathcal{P}$ . Fix an open  $U \subseteq \mathbb{R}$ . Write  $\hat{f}^{-1}[U] = \bigcup_{n \in \mathbb{N}} F_n$  where  $F_n$  is closed in  $\mathcal{P} \times X$ . Then,

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

which is  $F_\sigma$ .  $\square$

Given  $A \subseteq Y^X$  and  $K \subseteq X$  we write  $A|_K := \{f|_K : f \in A\}$ , i.e., the set of all restrictions of functions in  $A$  to  $K$ . The following Theorem is a slightly more general version of Theorem 2.8.

**Theorem 2.11.** *Assume that  $\mathcal{P}$  is countable,  $X$  is a Polish space, and  $A \subseteq C_p(X, \mathbb{R}^{\mathcal{P}})$  is such that  $\pi_P \circ A$  is pointwise bounded for all  $P \in \mathcal{P}$ . The following are equivalent for every compact  $K \subseteq X$ :*

- (1)  $\overline{A|_K} \subseteq B_1(K, \mathbb{R}^{\mathcal{P}})$ .
- (2)  $\pi_P \circ A|_K$  has the NIP for every  $P \in \mathcal{P}$ .

*Proof.* (1) $\Rightarrow$ (2). Let  $P \in \mathcal{P}$ . Fix  $\{f_n\}_{n \in \mathbb{N}} \subseteq A$  and  $a < b$ . By (1), we have  $\overline{A|_K} \subseteq B_1(K, \mathbb{R}^{\mathcal{P}})$ . Applying the homeomorphism  $f \mapsto \hat{f}$  and using lemma 2.10 we get  $\hat{A}|_{\mathcal{P} \times K} \subseteq B_1(\mathcal{P} \times K)$ . By Theorem 2.8, 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

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

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

(2) $\Rightarrow$ (1) Fix  $f \in \overline{A|_K}$ . By lemma 2.9 it suffices to show that  $\pi_P \circ f \in B_1(K)$  for all  $P \in \mathcal{P}$ . By (2),  $\pi_P \circ A|_K$  has the NIP. Hence, by Theorem 2.8 we have  $\overline{\pi_P \circ A|_K} \subseteq B_1(K)$ . But then  $\pi_P \circ f \in \overline{\pi_P \circ A|_K} \subseteq B_1(K)$ .  $\square$

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

**Lemma 2.12.** *Assume that  $X$  is Hausdorff and that  $A \subseteq C_p(X)$ . The following are equivalent for every  $L \subseteq X$ :*

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

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

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

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

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

By definition of closure:

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

This contradicts (i).  $\square$



## 3. NIP IN THE CONTEXT OF COMPUTATION

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

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

$$L[\mathbf{r}_{\bullet}] = L \cap \prod_{p \in \mathcal{P}} [-r_p, r_p]$$

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.

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

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

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

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

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

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

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

- (1)  $\overline{\tilde{\Delta}|_{\mathcal{L}[r_\bullet]}} \subseteq B_1(\mathcal{L}[r_\bullet], \mathcal{L}[r_\bullet])$  for all  $r_\bullet \in R$ .
- (2)  $\pi_P \circ \tilde{\Delta}|_{L[r_\bullet]}$  has the NIP for all  $P \in \mathcal{P}$  and  $r_\bullet \in R$ , that is, for all  $P \in \mathcal{P}$ ,  $r_\bullet \in R$ ,  $a < b$ ,  $\{\gamma_n\}_{n \in \mathbb{N}} \subseteq \Delta$  there are finite disjoint  $E, F \subseteq \mathbb{N}$  such that

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

Moreover, if any (hence all) of the preceding conditions hold, then every deep computation  $f \in \bar{\Delta}$  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, then  $\mathcal{L}[r_\bullet] \subseteq \mathbb{R}^{\mathcal{P}}$  is Polish. Also, the Extendibility Axiom implies that  $\pi_P \circ \tilde{\Delta}|_{\mathcal{L}[r_\bullet]}$  is a pointwise bounded set of continuous functions

for all  $P \in \mathcal{P}$ . Hence, Theorem 2.11 and Lemma 2.12 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  $\mathbf{r}_\bullet \in \mathbf{R}$  we have  $\tilde{f}|_{\mathcal{L}[\mathbf{r}_\bullet]} \in \overline{\tilde{\Delta}}|_{\mathcal{L}[\mathbf{r}_\bullet]} \subseteq B_1(\mathcal{L}[\mathbf{r}_\bullet], \mathcal{L}[\mathbf{r}_\bullet])$ . 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]).  $\square$

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

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

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

- (i)  $\text{NIP}_1$  if  $\overline{\tilde{\Delta}}|_{\mathcal{L}[\mathbf{r}_\bullet]}$  is first countable for every  $\mathbf{r}_\bullet \in \mathbf{R}$ .
- (ii)  $\text{NIP}_2$  if  $\overline{\tilde{\Delta}}|_{\mathcal{L}[\mathbf{r}_\bullet]}$  is hereditarily separable for every  $\mathbf{r}_\bullet \in \mathbf{R}$ .
- (iii)  $\text{NIP}_3$  if  $\overline{\tilde{\Delta}}|_{\mathcal{L}[\mathbf{r}_\bullet]}$  is metrizable for every  $\mathbf{r}_\bullet \in \mathbf{R}$ .

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

- (1) *Alexandroff compactification of a discrete space of size continuum.* For each  $\mathbf{a} \in 2^{\mathbb{N}}$  consider the map  $\delta_{\mathbf{a}} : 2^{\mathbb{N}} \rightarrow \mathbb{R}$  given by  $\delta_{\mathbf{a}}(\mathbf{x}) = 1$  if  $\mathbf{x} = \mathbf{a}$  and  $\delta_{\mathbf{a}}(\mathbf{x}) = 0$  otherwise. Let  $A(2^{\mathbb{N}}) = \{\delta_{\mathbf{a}} : \mathbf{a} \in 2^{\mathbb{N}}\} \cup \{0\}$ , where  $0$  is the zero map. Notice that  $A(2^{\mathbb{N}})$  is a compact subset of  $B_1(2^{\mathbb{N}})$ , in fact  $\{\delta_{\mathbf{a}} : \mathbf{a} \in 2^{\mathbb{N}}\}$  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  $\mathbf{v}_s : 2^{\mathbb{N}} \rightarrow \mathbb{R}$  be given by  $\mathbf{v}_s(\mathbf{x}) = 1$  if  $\mathbf{x}$  extends  $s$  and  $\mathbf{v}_s(\mathbf{x}) = 0$  otherwise. Let  $\hat{A}(2^{\mathbb{N}})$  be the pointwise closure of  $\{\mathbf{v}_s : s \in 2^{<\mathbb{N}}\}$ , i.e.,  $\hat{A}(2^{\mathbb{N}}) = A(2^{\mathbb{N}}) \cup \{\mathbf{v}_s : s \in 2^{<\mathbb{N}}\}$ . 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  $\mathbf{a} \in 2^{\mathbb{N}}$  let  $\mathbf{f}_{\mathbf{a}}^- : 2^{\mathbb{N}} \rightarrow \mathbb{R}$  be given by

435  $f_a^-(x) = 1$  if  $x < a$  and  $f_a^-(x) = 0$  otherwise. Let  $f_a^+ : 2^{\mathbb{N}} \rightarrow \mathbb{R}$  be given  
 436 by  $f_a^+(x) = 1$  if  $x \leq a$  and  $f_a^+(x) = 0$  otherwise. The split Cantor is the  
 437 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  
 438 compactum. One example of a countable dense subset is the set of all  $f_a^+$   
 439 and  $f_a^-$  where  $a$  is an infinite binary sequence that is eventually constant.  
 440 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:

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

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

441 Let  $D(K) = \{g_a^0 : a \in K\} \cup \{g_a^1 : a \in K\}$ . Notice that  $D(K)$  is a first  
 442 countable Rosenthal compactum. It is not separable if  $K$  is uncountable.  
 443 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

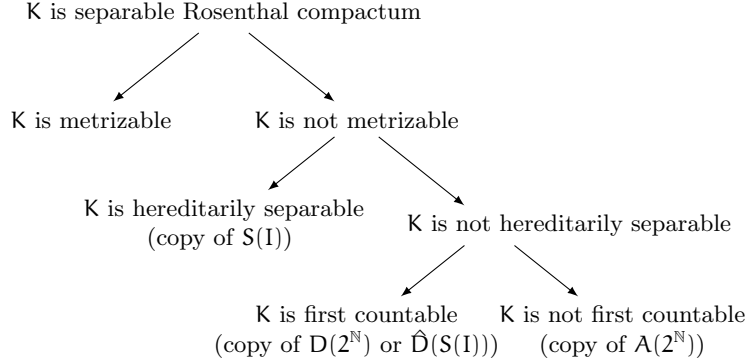
$$h_t(x) = \begin{cases} 0, & x < a_t \\ 1/2, & a_t \leq x \leq b_t \\ 1, & b_t < x \end{cases}$$

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

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

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

454 In other words, we have the following classification:



455

456 Lastly, the definitions provided here for  $\text{NIP}_i$  ( $i = 1, 2, 3$ ) are topological.

457 **Question 3.4.** Is there a non-topological characterization for  $\text{NIP}_i$ ,  $i = 1, 2, 3$ ?

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

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

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

474 **Definition 3.6.** Given a Polish space  $X$  and a pointwise bounded family  $\{f_t : t \in$   
 475  $2^{<\mathbb{N}}\}$ . We say that  $\{f_t : t \in 2^{<\mathbb{N}}\}$  is *minimal* if and only if for every dyadic subtree  
 476  $\{s_t : t \in 2^{<\mathbb{N}}\}$  of  $2^{<\mathbb{N}}$ ,  $\{f_{s_t} : t \in 2^{<\mathbb{N}}\}$  is equivalent to  $\{f_t : t \in 2^{<\mathbb{N}}\}$ .

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

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

- 491 (1)  $D_1 = \{\frac{1}{|t|+1} v_t : t \in 2^{<\mathbb{N}}\}$ . This is discrete in  $\overline{D_1} = A(2^{\mathbb{N}})$ .  
 492 (2)  $D_2 = \{s_t \widehat{0}^\infty : t \in 2^{<\mathbb{N}}\}$ . This is discrete in  $\overline{D_2} = 2^{\leq \mathbb{N}}$ .  
 493 (3)  $D_3 = \{f_{s_t \widehat{0}^\infty}^+ : t \in 2^{<\mathbb{N}}\}$ . This is a discrete in  $\overline{D_3} = S(2^{\mathbb{N}})$ .  
 494 (4)  $D_4 = \{f_{s_t \widehat{1}^\infty}^- : t \in 2^{<\mathbb{N}}\}$ . This is discrete in  $\overline{D_4} = S(2^{\mathbb{N}})$ .  
 495 (5)  $D_5 = \{v_t : t \in 2^{<\mathbb{N}}\}$ . This is discrete in  $\overline{D_5} = \widehat{A}(2^{\mathbb{N}})$ .  
 496 (6)  $D_6 = \{(v_{s_t}, s_t \widehat{0}^\infty) : t \in 2^{<\mathbb{N}}\}$ . This is discrete in  $\overline{D_6} = \widehat{D}(2^{\mathbb{N}})$ .  
 497 (7)  $D_7 = \{(v_{s_t}, x_{s_t \widehat{0}^\infty}^+) : t \in 2^{<\mathbb{N}}\}$ . This is discrete in  $\overline{D_7} = \widehat{D}(S(2^{\mathbb{N}}))$

498 **Theorem 3.7** (Heptacotomy of minimal families, Theorem 2 in [ADK08]). *Let*  
 499  *$X$  be Polish. For every relatively compact  $\{f_t : t \in 2^{<\mathbb{N}}\} \subseteq B_1(X)$ , there exists  $i =$*   
 500  *$1, 2, \dots, 7$  and a regular dyadic subtree  $\{s_t : t \in 2^{<\mathbb{N}}\}$  of  $2^{<\mathbb{N}}$  such that  $\{f_{s_t} : t \in 2^{<\mathbb{N}}\}$*   
 501 *is equivalent to  $D_i$ . Moreover, all  $D_i$  are minimal and mutually non-equivalent.*

502 **3.2. NIP and definability by universally measurable functions.** We now  
 503 turn to the question: what happens when  $\mathcal{P}$  is uncountable? Notice that the count-  
 504 ability assumption is crucial in the proof of Theorem 2.11 essentially because it  
 505 makes  $\mathbb{R}^{\mathcal{P}}$  a Polish space. For the uncountable case, we may lose Baire-1 definabil-  
 506 ity so we shall replace  $B_1(X)$  by a bigger class. Recall that the purpose of studying  
 507 the class of Baire-1 functions is that a pointwise limit of continuous functions is not  
 508 necessarily continuous. In [BFT78], J. Bourgain, D.H. Fremlin and M. Talagrand  
 509 characterized the Non-Independence Property of a set of continuous functions with  
 510 various notions of compactness in function spaces containing  $C(X)$ , such as  $B_1(X)$ .  
 511 In this section we will replace  $B_1(X)$  with the larger space  $M_r(X)$  of universally  
 512 measurable functions. The development of this section is based on Theorem 2F in  
 513 [BFT78]. We now give the relevant definitions. Readers with little familiarity with  
 514 measure theory can review the appendix for standard definitions appearing in this  
 515 subsection.

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

532 **Lemma 3.8.** *Let  $X$  be a Hausdorff space and  $Y = \prod_{i \in I} Y_i$  be any product of*  
 533 *measurable spaces  $(Y_i, \Sigma_i)$  for  $i \in I$ . Let  $\Sigma_Y$  be the cylinder  $\sigma$ -algebra generated by*  
 534 *the measurable spaces  $(Y_i, \Sigma_i)$ . Let  $f : X \rightarrow Y$ . The following are equivalent:*

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

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

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

548 **Definition 3.9.** Let  $(L, \mathcal{P}, \Gamma)$  be a CCS. We say that a transition  $f : L \rightarrow L$  is  
 549 *universally measurable shard-definable* if and only if there exists  $\tilde{f} : \mathcal{L}_{sh} \rightarrow \mathcal{L}_{sh}$   
 550 extending  $f$  such that for every sizer  $\mathbf{r}_\bullet$  there is a sizer  $\mathbf{s}_\bullet$  such that the restriction  
 551  $\tilde{f}|_{\mathcal{L}[\mathbf{r}_\bullet]} : \mathcal{L}[\mathbf{r}_\bullet] \rightarrow \mathcal{L}[\mathbf{s}_\bullet]$  is universally measurable, i.e.  $\pi_P \circ \tilde{f}|_{\mathcal{L}[\mathbf{r}_\bullet]} : \mathcal{L}[\mathbf{r}_\bullet] \rightarrow [-s_P, s_P]$   
 552 is  $\mu$ -measurable for every Radon probability measure  $\mu$  on  $\mathcal{L}[\mathbf{r}_\bullet]$ .

553 We will need the following result about NIP and universally measurable func-  
 554 tions:

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

- 557 (i)  $\overline{A} \subseteq M_r(X)$ .  
 558 (ii) For every compact  $K \subseteq X$ ,  $A|_K$  has the NIP.  
 559 (iii) For every Radon measure  $\mu$  on  $X$ ,  $A$  is relatively countably compact in  
 560  $\mathcal{L}^0(X, \mu)$ , i.e., every countable subset of  $A$  has an accumulation point in  
 561  $\mathcal{L}^0(X, \mu)$ .

562 Theorem 2.8 immediately yields the following.

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

567 *Proof.* By the Extendibility Axiom, Theorem 2.8 and lemma 2.12 we have that  
 568  $\pi_P \circ \tilde{\Delta}|_{\mathcal{L}[\mathbf{r}_\bullet]} \subseteq M_r(\mathcal{L}[\mathbf{r}_\bullet])$  for all  $\mathbf{r}_\bullet \in R$  and  $P \in \mathcal{P}$ . Let  $f \in \overline{\Delta}$  be a deep computation.  
 569 Write  $f = \mathcal{U} \lim_i \gamma_i$  as an ultralimit of computations in  $\Delta$ . Define  $\tilde{f} := \mathcal{U} \lim_i \tilde{\gamma}_i$ .  
 570 Then, for all  $\mathbf{r}_\bullet \in R$  and  $P \in \mathcal{P}$   $\pi_P \circ \tilde{\gamma}_i|_{\mathcal{L}[\mathbf{r}_\bullet]} \in M_r(\mathcal{L}[\mathbf{r}_\bullet])$  for all  $i$  so  $\pi_P \circ \tilde{f}|_{\mathcal{L}[\mathbf{r}_\bullet]} \in$   
 571  $\overline{M_r(\mathcal{L}[\mathbf{r}_\bullet])} \subseteq M_r(\mathcal{L}[\mathbf{r}_\bullet])$ .  $\square$

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

3.3. **Talagrand stability and definability by universally measurable functions.** There is another notion closely related to NIP, introduced by Talagrand in [Tal84] while studying Pettis integration. Suppose that  $X$  is a compact Hausdorff space and  $A \subseteq \mathbb{R}^X$ . Let  $\mu$  be a Radon probability measure on  $X$ . Given a  $\mu$ -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  $\mu$ -stable* if and only if for every  $\mu$ -measurable set  $E \subseteq X$  of positive measure and for every  $a < b$  there is  $k \geq 1$  such that  $(\mu^{2k})^*(D_k(A, E, a, b)) < (\mu(E))^{2k}$ . Notice that we work with the outer measure because it is not necessarily true that the sets  $D_k(A, E, a, b)$  are  $\mu$ -measurable. This is certainly the case when  $A$  is a countable set of continuous (or  $\mu$ -measurable) functions.

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

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

*Proof.* First, observe that a subset of a  $\mu$ -stable set is  $\mu$ -stable. To show that  $\overline{A}$  is  $\mu$ -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  $\mu$ -measurable set with positive measure. It suffices to show that  $\overline{A} \subseteq \mathcal{L}^0(X, \mu)$ . Suppose that there exists  $f \in \overline{A}$  such that  $f \notin \mathcal{L}^0(X, \mu)$ . By a characterization of measurable functions (see 413G in [Fre03]), there exists a  $\mu$ -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  $\mu$ -stable, but we argued before that a subset of a  $\mu$ -stable set must be  $\mu$ -stable.  $\square$

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

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

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

**Lemma 3.15** (Fremlin's Dichotomy, 463K in [Fre03]). *If  $(X, \Sigma, \mu)$  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 the measure theoretic version of Rosenthal's Dichotomy. Combining this dichotomy with the Theorem 3.10 we get the following result:

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

- (i)  $\overline{A} \subseteq M_r(X)$ .
- (ii) For every compact  $K \subseteq X$ ,  $A|_K$  has the NIP.
- (iii) For every Radon measure  $\mu$  on  $X$ ,  $A$  is relatively countably compact in  $\mathcal{L}^0(X, \mu)$ , i.e., every countable subset of  $A$  has an accumulation point in  $\mathcal{L}^0(X, \mu)$ .
- (iv) For every Radon measure  $\mu$  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 3.10. Notice that the equivalence of (iii) and (iv) is Fremlin's Dichotomy Theorem.  $\square$

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

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

**Question 3.18.** Is the converse true?

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

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

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

## APPENDIX: MEASURE THEORY

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

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

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

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

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

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

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

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

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

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