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► **To cite this version:**

Hugo Férée, Mathieu Hoyrup, Walid Gomaa. On the query complexity of real functionals. LICS - 28th ACM/IEEE Symposium on Logic in Computer Science, Jun 2013, New Orleans, United States. pp.103-112, 2013, <<http://www.computer.org/csdl/proceedings/lics/2013/5020/00/5020a103-abs.html>>. <10.1109/LICS.2013.15>. <hal-00773653>

**HAL Id: hal-00773653**

**<https://hal.inria.fr/hal-00773653>**

Submitted on 14 Jan 2013

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# On the query complexity of real functionals

Hugo Férée, Walid Gomaa and Mathieu Hoyrup

January 14, 2013

## Abstract

Recently Kawamura and Cook developed a framework to define the computational complexity of operators arising in analysis. Our goal is to understand the effects of complexity restrictions on the analytical properties of the operator. We focus on the case of norms over  $\mathcal{C}[0, 1]$  and introduce the notion of *dependence* of a norm on a point and relate it to the query complexity of the norm. We show that the dependence of almost every point is of the order of the query complexity of the norm. A norm with small complexity depends on a few points but, as compensation, highly depends on them. We characterize the functionals that are computable using one oracle call only and discuss the uniformity of that characterization.

## 1 Introduction

An approach to computable analysis is the so-called *Type-Two Theory of Effectivity (TTE)* which enables one to extend computability theory from discrete spaces to many continuous spaces arising in mathematical analysis [Wei00, BHW08]. On the other side, computational complexity theory over continuous spaces is still in its infancy. A theory applicable to the space of real numbers has been developed by Ko and Friedman [KF82, Ko91] and has given many results. However, this theory is not readily extendible to “larger” spaces such as the space  $\mathcal{C}[0, 1]$  of continuous real functions defined over the unit interval, and a more general, abstract theory is still lacking. First approaches have been developed by Weihrauch [Wei03] on metric spaces, and by Schröder [Sch04] who argues that in order to express computational complexity in terms of first-order time functions (as in the discrete setting), one must restrict to  $\sigma$ -compact spaces. Recently Kawamura and Cook [KC10] developed a framework applicable to the space  $\mathcal{C}[0, 1]$  (which is not  $\sigma$ -compact), using higher-order complexity theory and in particular second-order polynomials. In particular their theory enables them to prove uniform versions of older results about the complexity of solving differential equations, as well as new results [Kaw10, KORZ12].

Our general goal is to study the complexity of operators defined over  $\mathcal{C}[0,1]$  and particularly to understand the implication that complexity restrictions have on the analytical properties of the operator. Looking for connections between computation and analysis is an old and fruitful field of investigation. The most famous example is the fact that on many sorts of topological spaces, a computable function must be continuous and, further, the continuous functions are exactly the functions that are computable relative to some oracle. Topology is always hidden behind computability notions, which explains why higher-order recursion theory and computable analysis are intimately related to descriptive set theory. Such a correspondence between computation and topology also comes up in complexity theory: bounds on the resources available during the computation are reflected in analytical constraints over the functions to be computed, confining them to live in a smaller space. Illustrations of this principle appear in several places. Townsend [Tow90] characterized relativized polynomial classes of type-2 relations by means of topological notions: for instance if  $A$  is an alphabet then a subset of  $(A^*)^{A^*}$  is in  $\Sigma_1^P$  relative to some oracle (written  $\underline{\Sigma}_1^P$  in his paper) if and only if it is a “polynomially open set”, in a certain sense. In analysis, a real function  $f : [0,1] \rightarrow \mathbb{R}$  is polynomial-time computable relative to an oracle if and only if it has a polynomial modulus of uniform continuity [Ko91].

This paper is a first study along these lines of the complexity theory over  $\mathcal{C}[0,1]$  recently developed by Kawamura and Cook, in which such correspondences are not known to date. Some typical questions are: what are the topological implications of limiting the resources of a machine computing a functional? what is the class of functionals that are computable in polynomial time relative to an oracle? Observe that a bound on a resource such as time imposes two conditions on the machine operation: it restricts its internal computation time as well as the information queried to the oracle. We mostly concentrate on the second constraint, expressed in terms of *query complexity*.

The potential limitations imposed by resource bounds on the computation of functionals over  $\mathcal{C}[0,1]$  come from the representation of input functions  $f \in \mathcal{C}[0,1]$  which does not give a global view on  $f$  but local information only: the whole function is not approximated, for example, by piecewise linear functions, but rather the oracle evaluates the function on demand at queried points, in addition to giving a modulus of continuity of  $f$  to the machine. The penny-pinching character of the oracle describing the input is due to the huge amount of information a function contains (one can see [Far11] for a quantitative analysis of this fact). As a result, little can be known about  $f$  in polynomial time, and classical operators such as taking the supremum or the integral of a function are not polynomial-time computable because a machine needs exponential time to evaluate its input on the whole interval.

In this paper, we do not consider general functionals but we focus on the simpler case of norms over  $\mathcal{C}[0,1]$ . The general problem is: what are the analytical effects of bounding the computational resources to compute a norm? As explained above, bounding the allowed number of queries to the oracle prevents the machine to evaluate its input  $f \in \mathcal{C}[0,1]$  at too many points, hence a norm with low query complexity should “depend” on a small set. We formalize this idea by introducing two notions: the quantitative notion of *dependence of a norm on a point* and the qualitative notion of *relevance of a point w.r.t. a norm*. Intuitively, a norm  $\|\cdot\|$  has high dependence on a point if changing  $f$  around that point results in a big change in the value  $\|f\|$ . We then show how the query complexity of the norm impacts on these properties: a norm with low complexity depends on a small set but, as compensation, the dependence on that set is very high.

We also investigate the extreme case when only one oracle call is allowed to the machine computing a functional and obtain a characterization. Surprisingly, the argument to obtain such a characterization is much more involved than expected. It contains subtleties that make it non-uniform in terms of complexity.

The paper is organized as follows. In Section 2 we present the background on complexity in analysis needed for our results. In Section 3 we formalize the notions of *dependence* of a norm on a point and of *relevant* points w.r.t. a norm. We then show how they reflect the query complexity of the norm. In Section 4 we characterize the class of functionals that are computable by an oracle Turing machine making only one query to the oracle. In Section 5 we conclude the paper with open questions to be investigated in the future. Proofs of three results are put in the appendix.

## 2 Definitions and Preliminary Results

### 2.1 Notations and basic definitions

$\Sigma$  denotes the alphabet  $\{0,1\}$ . The length of a finite word  $u$  over  $\Sigma$  is denoted by  $|u|$ .

Let  $A \subseteq [0,1]$  and  $\beta \in [0,1]$ . The distance of  $\beta$  to  $A$  is  $d(\beta, A) = \inf\{|\alpha - \beta| : \alpha \in A\}$ . Given  $r > 0$ , the neighborhood of  $A$  of radius  $r$  is  $N(A, r) = \{\beta \in [0,1] : d(\beta, A) < r\}$ . If  $\alpha \in [0,1]$ , we simply write  $N(\alpha, r) = N(\{\alpha\}, r) = \{\beta \in [0,1] : |\alpha - \beta| < r\}$ . We will also consider the closed neighborhood  $\overline{N}(A, r) = \{\beta : d(\beta, A) \leq r\}$ .

We assume the space  $\mathcal{C}[0,1]$  of continuous functions from  $[0,1]$  to  $\mathbb{R}$  with the usual structure of real vector space. The uniform norm is defined by  $\|f\|_\infty = \max_{x \in [0,1]} |f(x)|$ . The  $L^1$ -norm is defined by  $\|f\|_1 = \int_0^1 |f(x)| dx$ .

If  $f \in \mathcal{C}[0,1]$  then the **support** of  $f$  is  $\text{Supp}(f) = \{x \in [0,1] : f(x) \neq 0\}$ . Observe that  $\text{Supp}(f)$  is an open set. We say that  $f$  is **supported** on a set  $A \subseteq [0,1]$  if  $\text{Supp}(f) \subseteq A$ .

$\text{Lip}_1 \subseteq \mathcal{C}[0, 1]$  denotes the set of 1-Lipschitz functions from  $[0, 1]$  to  $\mathbb{R}$ .

A norm  $F$  over  $\mathcal{C}[0, 1]$  is *weaker* than a norm  $G$  if one there is a constant  $c$  such that  $F(f) \leq c \cdot G(f)$  for all  $f \in \mathcal{C}[0, 1]$ , or equivalently the functional  $F : \mathcal{C}[0, 1] \rightarrow \mathbb{R}$  is continuous w.r.t. the topology of the norm  $G$ .

## 2.2 Polynomial time computable functionals

We briefly recall the formalism of [KC10].

**Oracle Turing machine.** An oracle Turing machine  $\mathcal{M}$  taking as input a finite string  $u \in \Sigma^*$  and consulting an oracle given by a function  $\varphi : \Sigma^* \rightarrow \Sigma^*$  is denoted  $\mathcal{M}^\varphi(u)$ .

A function  $\varphi : \Sigma^* \rightarrow \Sigma^*$  is *regular* if  $|u| \leq |v|$  implies  $|\varphi(u)| \leq |\varphi(v)|$  for all  $u, v \in \Sigma^*$ . The *size* of a regular function  $\varphi$  is the function  $|\varphi| : \mathbb{N} \rightarrow \mathbb{N}$  defined by  $|\varphi|(n) = |\varphi(0^n)|$  (as  $\varphi$  is regular,  $0^n$  can be replaced by any word of length  $n$ ).

The pairing of two regular functions  $\varphi, \psi : \Sigma^* \rightarrow \Sigma^*$  is the regular function  $\langle \varphi, \psi \rangle$  defined by  $\langle \varphi, \psi \rangle(0u) = \varphi(u)10^{|\psi(u)|}$  and  $\langle \varphi, \psi \rangle(1u) = \psi(u)10^{|\varphi(u)|}$ .

**Polynomial time oracle Turing machine.** *Second-order polynomials* are defined inductively in the following way: every positive integer is a second-order polynomial, every first-order variable  $n$  is a second-order polynomial, if  $P$  and  $Q$  are second-order polynomials then so are  $P + Q$ ,  $PQ$  and  $X(P)$  where  $X$  is a second-order variable.

An oracle Turing machine  $\mathcal{M}$  *runs in polynomial time* if there is a second-order polynomial  $P(n, X)$  such that for any regular function  $\varphi$  and input  $u \in \Sigma^*$ ,  $\mathcal{M}^\varphi(u)$  halts in at most  $P(|u|, |\varphi|)$  steps.

**Representation of  $\mathcal{C}[0, 1]$ .** For  $n \in \mathbb{N}$ , let  $\mathbb{D}_n = \{\frac{p}{2^n} : p \in \mathbb{N}, 0 \leq p \leq 2^n\}$  and  $\mathbb{D} = \bigcup_n \mathbb{D}_n$  be the set of dyadic rational numbers in the interval  $[0, 1]$ . Every string  $u \in \Sigma^*$  represents a dyadic rational  $d_u$  whose binary expansion is  $0.u$ .

A *modulus of continuity* of a function  $f \in \mathcal{C}[0, 1]$  is a function  $\mu : \mathbb{N} \rightarrow \mathbb{N}$  such that if  $|x - y| \leq 2^{-\mu(n)}$  then  $|f(x) - f(y)| \leq 2^{-n}$ .

An *approximation function* of  $f$  is a function  $f_{\mathbb{D}} : \mathbb{D} \times \mathbb{N} \rightarrow \mathbb{D}$  such that  $|f_{\mathbb{D}}(d, n) - f(d)| \leq 2^{-n}$ . We can assume w.l.o.g. that  $f_{\mathbb{D}}(d, n) \in \mathbb{D}_n$ .

We represent  $\mu$  by the function  $\overline{\mu}(u) = 0^{\mu(|u|)}$ . We represent  $f_{\mathbb{D}}$  by the function  $\overline{f_{\mathbb{D}}} : \Sigma^* \times \Sigma^* \rightarrow \Sigma^*$  defined by  $\overline{f_{\mathbb{D}}}(u, v) = w$  such that  $d_w = f_{\mathbb{D}}(d_u, |v|)$ .

If  $\mu$  is a modulus of continuity of  $f$  and  $f_{\mathbb{D}}$  an approximation function of  $f$  then  $\langle \overline{\mu}, \overline{f_{\mathbb{D}}} \rangle$  is a *representation* of  $f$ .

A functional  $F : \mathcal{C}[0, 1] \rightarrow \mathbb{R}$  is computable if there is an oracle Turing machine  $\mathcal{M}$  such that for any  $f \in \mathcal{C}[0, 1]$ , any representation  $\varphi$  of  $f$  and any

$n \in \mathbb{N}$  written in unary notation,  $\mathcal{M}^\varphi(n)$  halts and outputs a dyadic number  $d$  such that  $|F(f) - d| \leq 2^{-n}$ .

A *relativized* oracle Turing machine is an oracle Turing machine that has access to an auxiliary oracle  $A \in \{0, 1\}^{\mathbb{N}}$  and queries  $A(n)$  by writing the binary expansion of  $n$  on an extra query tape. The representation of functions in  $\mathcal{C}[0, 1]$  is natural in the precise sense that it is *admissible*: a functional  $F : \mathcal{C}[0, 1] \rightarrow \mathbb{R}$  is computable by a relativized oracle Turing machine if and only if it is continuous w.r.t. the topology of the uniform norm (see [Wei00] for precise results on admissibility of representations). In particular, a norm is computable by relativized oracle Turing machines if and only if it is weaker than the uniform norm.

**Definition 2.1.** A functional  $F : \mathcal{C}[0, 1] \rightarrow \mathbb{R}$  is polynomial-time computable if it is computable by an oracle Turing machine that runs in polynomial time.

*Example 2.1.* Assume  $(q_n)_{n \in \mathbb{N}}$  is a polynomial-time computable enumeration of the dyadic rational numbers in the interval  $[0, 1]$ , i.e. there is a polynomial-time computable function  $\psi : \Sigma^* \rightarrow \Sigma^*$  such that  $q_n = d_{\psi(0^n)}$ . Define the functional

$$F_0(f) = \sum_{n \in \mathbb{N}} \frac{|f(q_n)|}{2^n}.$$

$F_0$  is a norm over  $\mathcal{C}[0, 1]$ . It can be easily verified that  $F_0$  can be computed by a machine with computational time bounded by a second-order polynomial in terms of the size of (a representation of)  $f$  and the precision parameter.

### 3 Norms

Ko [Ko82] introduced the class  $\text{NP}_{\mathbb{R}}$  of NP real numbers and showed that it coincides with the class of maximum values of polynomial time computable functions over  $[0, 1]$ . The separation problem  $\text{P}_{\mathbb{R}} = \text{NP}_{\mathbb{R}}$  lies between the problems  $\text{P} = \text{NP}$  and  $\text{EXP} = \text{NEXP}$ . Friedman [Fri84] obtained similar results for the integral values of polynomial time computable functions. These results show that separating complexity classes of real numbers is as difficult as in the case of sets of strings. However the situation is different for complexity classes of functionals: Ko and Friedman [KF82] proved that the functional mapping  $f \in \mathcal{C}[0, 1]$  to  $\max\{f(x) : x \in [0, 1]\}$  is not polynomial-time computable (in a certain sense that is weaker than the one of Cook and Kawamura used here, Definition 2.1), while there is a way to express the fact that it is an NP functional. Similarly, the functional mapping  $f \in \mathcal{C}[0, 1]$  to  $\int_0^1 f(x) dx$  can be proved not to be polynomial-time computable.

The main reason why lower bounds are much easier to achieve in the case of functionals lies in the fact that time restrictions not only bound the internal computation time of a machine but also *limit its access to the input*

– it contrasts with the classical setting where time restrictions usually do not prevent the machine to access its input entirely. Hence a machine running in polynomial time does not have time enough to evaluate the input function on a large set so it can hardly distinguish between some very different functions. It suggests that if a machine computes a norm, bounding its computation time must have implications on the topology induced by the norm, which raises the following question: what are the topologies induced by polynomial-time computable norms?

We already know that they cannot be equivalent to the topologies of the uniform norm and the  $L^1$  norm. One can prove that (i) a polynomial-time computable norm is incomparable with the  $L^1$  norm, (ii) it cannot be complete, (iii) the notion of convergence it induces is incomparable with convergence in probability. Hence polynomial-time computable norms live in a reduced space, outlined by these properties. Our goal is to circumscribe more accurately complexity classes of norms by having a finer look into their analytical properties. The subsequent notions of *dependence* of a norm on a point and of *relevance* of a point w.r.t. a norm will make it possible.

### 3.1 Dependence of a norm on a point

Let  $F$  be a norm over  $\mathcal{C}[0, 1]$  and  $\alpha \in [0, 1]$ . Intuitively, one would say that the norm of a function depends on its value at  $\alpha$  if modifying it at  $\alpha$  *only* changes its norm. But two problems appear: first we consider continuous functions so modifying a function  $f$  at  $\alpha$  is not possible without modifying  $f$  also around  $\alpha$ ; second, if  $f = 0$  then modifying  $f$  anywhere will automatically change  $F(f) = 0$  to some positive value, as  $F$  is a norm. To get around these issues, the solution consists in defining a quantitative dependence notion that relates the size of the neighborhood of  $\alpha$  on which  $f$  is modified to the alteration of the value  $F(f)$ . As  $F$  is a norm, it has a certain homogeneity that allows us to focus on the function  $f = 0$  only.

From now on we assume that  $F$  is a norm over  $\mathcal{C}[0, 1]$  that is weaker than the uniform norm.

**Definition 3.1.** Let  $F$  be a norm on  $\mathcal{C}[0, 1]$  and  $\alpha \in [0, 1]$ . The *dependence* of  $F$  on  $\alpha \in [0, 1]$  is the function  $d_{F,\alpha} : \mathbb{N} \rightarrow \mathbb{R}$  defined by

$$\begin{aligned} d_{F,\alpha}(n) &= \sup\{l : \exists f \in \text{Lip}_1, \text{Supp}(f) \subseteq N(\alpha, 1/l) \\ &\quad \text{and } F(f) > 2^{-n}\} \\ &= \inf\{l : \forall f \in \text{Lip}_1, \text{Supp}(f) \subseteq N(\alpha, 1/l) \\ &\quad \text{implies } F(f) \leq 2^{-n}\}. \end{aligned}$$

Observe that the first set is downward closed, so the two definitions are equivalent.

For every  $\alpha$  and  $n$ ,  $d_{F,\alpha}(n) \geq 1$ . Indeed, if  $l < 1$  then every function is supported on  $N(\alpha, 1/l) = [0, 1]$ . For every  $\alpha$ ,  $d_{F,\alpha}$  is nondecreasing, unbounded and  $d_{F,\alpha}(n) \leq 2c \cdot 2^n$  if  $F \leq c \cdot \|\cdot\|_\infty$ .

One easily checks that the set  $\{l : \forall f \in \text{Lip}_1, \text{Supp}(f) \subseteq N(\alpha, 1/l) \text{ implies } F(f) \leq 2^{-n}\}$  is closed, so the infimum is a minimum.

Let  $h_{\alpha,r}$  be the maximal 1-Lipschitz function supported on  $N(\alpha, r)$ . When the norm is monotonic, i.e.  $|f| \leq |g|$  implies  $F(f) \leq F(g)$ ,

$$d_{F,\alpha}(n) = \sup \{l : F(h_{\alpha,1/l}) > 2^{-n}\}.$$

Let us illustrate Definition 3.1 on a few examples.

*Example 3.1.* Let  $F$  be the uniform norm. For all  $\alpha \in [0, 1]$  and  $n \in \mathbb{N}$ ,  $2^n \leq d_{F,\alpha}(n) \leq 2^{n+1}$ . The dependence of a point w.r.t. to the uniform norm is maximal.

*Example 3.2.* Let  $F$  be the  $L^1$  norm. For all  $\alpha \in [0, 1]$  and  $n \in \mathbb{N}$ ,  $2^{\frac{n-1}{2}} \leq d_{F,\alpha}(n) \leq 2^{\frac{n+1}{2}}$ . While exponential, the dependence of a point w.r.t. the  $L^1$  norm is smaller than for the uniform norm.

*Example 3.3.* Let  $Q = \{q_0, q_1, \dots\} \subseteq [0, 1]$  be a countable dense set and  $F(f) = \sum_i 2^{-i} |f(q_i)|$ . For all  $i$  and  $n \geq i$ ,  $d_{F,q_i}(n) \geq 2^{n-i}$ : intuitively, the norm of a function depends much on its value on  $Q$ . Moreover, it does not depend much on points that are ‘‘far away’’ from the points  $q_i$  and the dependence of almost every point (in the sense of Lebesgue measure) is bounded by a polynomial. Indeed, let  $\alpha$  be such that  $|\alpha - q_i| \geq \epsilon/i^2$  for all  $i$ : one has  $d_{F,\alpha}(n) \leq n^2/\epsilon$  for all  $n$ . To show that, let  $f \in \text{Lip}_1$  with  $\text{Supp}(f) \subseteq N(\alpha, \epsilon/n^2)$ .  $f$  is null on  $\{q_0, \dots, q_n\}$  so  $F(f) = \sum_{i>n} 2^{-i} |f(q_i)| \leq 2^{-n}$  as  $\|f\|_\infty \leq 1$ . Observe that the set of such  $\alpha$  has measure  $\geq 1 - \epsilon\pi^2/3$  which can be made arbitrarily close to 1. So for  $\alpha$  in a set of measure 1,  $d_{F,\alpha}$  is bounded by a polynomial (which depends on  $\alpha$ ).

**Proposition 3.1.** *For each  $n \in \mathbb{N}$ , the function  $\alpha \mapsto d_{F,\alpha}(n)$  is continuous. Moreover one has for all  $\alpha, \beta$ ,*

$$|d_{F,\alpha}(n) - d_{F,\beta}(n)| \leq |\alpha - \beta| d_{F,\alpha}(n) d_{F,\beta}(n).$$

*Proof.* Let  $l < d_{F,\alpha}(n)$ ,  $f \in \text{Lip}_1$  with  $\text{Supp}(f) \subseteq N(\alpha, 1/l)$  and  $F(f) > 2^{-n}$ .  $\text{Supp}(f) \subseteq N(\beta, 1/l + |\alpha - \beta|)$  so  $d_{F,\beta}(n) \geq l/(1 + l|\alpha - \beta|)$ . As it is true for every  $l < d_{F,\alpha}(n)$ ,  $d_{F,\beta}(n) \geq d_{F,\alpha}(n)/(1 + d_{F,\alpha}(n)|\alpha - \beta|)$  so  $d_{F,\alpha}(n) - d_{F,\beta}(n) \leq |\alpha - \beta| d_{F,\alpha}(n) d_{F,\beta}(n)$ . Exchanging  $\alpha$  and  $\beta$  gives the result. As  $d_{F,\alpha}(n)$  is bounded by  $c \cdot 2^n$  for some  $c$ , it implies that  $\alpha \mapsto d_{F,\alpha}(n)$  is continuous.  $\square$

**Proposition 3.2.** *If a norm  $F$  is weaker than a norm  $G$  then there exists  $k$  such that for all  $\alpha$  and  $n$ ,  $d_{F,\alpha}(n) \leq d_{G,\alpha}(n + k)$ .*

*Proof.* Straightforward from the definition, using  $k$  such that  $F \leq 2^k G$ .  $\square$



However, non equivalent norms may not be distinguished by their dependence functions. If  $F$  is a norm then  $F(f) + |f(0) - f(1)|$  and  $F(f) + |f(0)| + |f(1)|$  are generally non-equivalent but have exactly the same dependence functions.

**Definition 3.2.** The *maximal dependence* of a norm  $F$  is the function  $D_F : \mathbb{N} \rightarrow \mathbb{R}$  defined by

$$D_F(n) = \max_{\alpha \in [0,1]} d_{F,\alpha}(n).$$

For every norm that is weaker than the uniform norm, there exists a constant  $c$  such that  $D_F(n) \leq c \cdot 2^n$ . The next result gives a lower bound, which is optimal as it is reached by the  $L^1$  norm.

**Proposition 3.3.** *For every norm  $F$  there exists  $c > 0$  such that  $D_F(n) \geq c \cdot 2^{\frac{n}{2}}$  for all  $n$ .*

*Proof.* Let  $\mathbb{N} \in \mathbb{N} \setminus \{0\}$ . One easily checks that the sum  $\sum_{i=0}^N h_{i/N,1/N}$  equals the constant function  $\frac{1}{N}$ . By triangular inequality,  $\frac{F(1)}{N} \leq \sum_i F(h_{i/N,1/N}) \leq (N+1) \max_i F(h_{i/N,1/N})$  so there exists  $i \in \{0, \dots, N\}$  such that  $F(h_{i/N,1/N}) \geq \frac{F(1)}{N(N+1)}$ . Let  $0 < c < \sqrt{F(1)}/4$  and  $N = \lceil c2^{\frac{n}{2}} \rceil$ . One has  $\frac{F(1)}{N(N+1)} > \frac{F(1)}{(N+1)^2} > 2^{-n}$  if  $n$  is sufficiently large, so  $D_F(n) \geq d_{F,\frac{i}{N}}(n) \geq N \geq c2^{\frac{n}{2}}$ . Changing  $c$  one can obtain the inequality for all  $n$ .  $\square$

As we will see later (Proposition 3.4), this bound is reached by some point  $\alpha$ .

Each point of high dependence has an influence on the value of the norm, but does not usually determine that value. However, the next theorem shows that the whole set of points of high dependence taken together determine the value of the norm up to some precision. Let

$$R_{n,l} = \{\alpha : d_{F,\alpha}(n) \geq l\}.$$

As  $\alpha \mapsto d_{F,\alpha}(n)$  is continuous,  $R_{n,l}$  is a closed set.

**Theorem 3.1.** *Let  $l \leq D_F(n)$ . If  $f \in \text{Lip}_1$  is null on  $R_{n,l}$  then  $F(f) \leq l^2 2^{-n+6}$ .*

*Proof idea.* Decompose  $f$  as a sum of small functions supported on intervals of length at most  $2/l$ . Each small function is supported on a small neighborhood of radius  $1/l$  of some point  $\alpha$  satisfying  $d_{F,\alpha}(n) \leq l$ , so the norm of each small function is at most  $2^{-n}$ . The number of small functions is quadratic in  $l$ , which gives the result.  $\square$

This result gives a strategy to evaluate the norm of a function. Indeed, let  $\epsilon > 0$  and  $l = 2^{-\frac{n-7}{2}} \sqrt{\epsilon}$ . Theorem 3.1 implies that if  $f, g \in \text{Lip}_1$  coincide on  $R_{n,l}$  then  $|F(f) - F(g)| \leq F(f-g) \leq \epsilon$  (applying the theorem to  $\frac{f-g}{2} \in \text{Lip}_1$ ) so in order to know the norm of  $f$  up to  $\epsilon$ , it is sufficient to evaluate  $f$  on  $R_{n,l}$ .

### 3.2 Relevant points

Intuitively, the norm of a function  $f$  depends on the values of  $f$  on points of high dependence, i.e. points  $\alpha$  whose function  $d_{F,\alpha}$  is large. Several questions arise: at which points a machine computing a norm should evaluate its input function? can we separate the points into two classes, the points that are relevant to compute the norm and the points that are not, according to the growth of their dependence function? To answer the second question, we need to find a threshold. The example of the  $L^1$  norm shows that one cannot hope in general to have points whose dependence function grows faster than  $2^{\frac{n}{2}}$ , so the threshold should be at most of the order of  $2^{\frac{n}{2}}$ . Proposition 3.3 suggests (but does not imply) that points whose dependence is at least  $2^{\frac{n}{2}}$  might always exist. It is indeed the case as Proposition 3.4 below shows. We can then choose  $2^{\frac{n}{2}}$  as a threshold that separates  $[0, 1]$  into the two classes of *relevant* and *irrelevant* points. The interest of these notions will be demonstrated by Theorem 3.2, 3.3 and 3.4.

**Definition 3.3.** Let  $F$  be a norm over  $\mathcal{C}[0, 1]$ . A point  $\alpha$  is *relevant* w.r.t.  $F$  if there exists  $c > 0$  such that  $d_{F,\alpha}(n) \geq c \cdot 2^{\frac{n}{2}}$  for all  $n$ .

First observe that the set  $\mathcal{R}$  of relevant points is a countable union of growing compact sets,

$$\mathcal{R}_k = \{\alpha : \forall n, d_{F,\alpha}(n) \geq 2^{\frac{n}{2}-k}\} = \bigcap_n \mathcal{R}_{n, 2^{\frac{n}{2}-k}}$$

$$\mathcal{R} = \bigcup_k \mathcal{R}_k.$$

As  $d_{F,\alpha}(n) \geq 1$  for all  $\alpha$  and  $n$ ,  $\mathcal{R}_k = \{\alpha : \forall n > 2k, d_{F,\alpha}(n) \geq 2^{\frac{n}{2}-k}\}$ .

Proposition 3.3 can be strengthened: relevant points always exist and are dense, which fits with the intuition that a norm should “look everywhere” to separate different functions.

**Proposition 3.4.** Let  $F$  be a norm. The set of relevant points is dense.

*Proof.* Let  $p \in \mathbb{N} \setminus \{0\}$  and  $a \in [2^{-p}, 1 - 2^{-p}]$ . We construct a relevant point  $\alpha \in \overline{N}(a, 2^{-p})$ . Let  $c \in \mathbb{N}$  be such that  $F(h_{a, 2^{-p}}) > 2^{-c}$ .  $\alpha$  will be the limit of a sequence  $\alpha_n$  defined by induction on  $n$ , satisfying  $F(h_{\alpha_n, 2^{-n-p}}) > 2^{-2n-c}$ . Start with  $\alpha_0 = a$ .

Given  $\alpha_n$ , we decompose  $h_{\alpha_n, 2^{-n-p}}$  as a sum of four functions (see Figure 1). Let  $\beta_1 = \beta_2 = \alpha_n$ ,  $\beta_3 = \alpha_n - 2^{-n-p-1}$  and  $\beta_4 = \alpha_n + 2^{-n-p-1}$ .  $h_{\alpha_n, 2^{-n-p}} = \sum_{i=1}^4 h_{\beta_i, 2^{-n-p-1}}$  so by triangular inequality there exists  $\alpha_{n+1} \in \{\beta_1, \beta_2, \beta_3, \beta_4\}$  such that  $F(h_{\alpha_{n+1}, 2^{-n-p-1}}) \geq F(h_{\alpha_n, 2^{-n-p}})/4 > 2^{-2n-2-c}$ .

As  $|\alpha_n - \alpha_{n+1}| \leq 2^{-n-p-1}$ ,  $\alpha_n$  is a Cauchy sequence, let  $\alpha$  be its limit. One has  $|\alpha - \alpha_n| \leq 2^{-n-p}$  so  $h_{\alpha_n, 2^{-n-p}}$  is supported on  $N(\alpha, 2^{-n-p+1})$ . As  $F(h_{\alpha_n, 2^{-n-p}}) > 2^{-2n-c}$ ,  $d_{F,\alpha}(2n+c) \geq 2^{n+p-1}$ . Let  $k \geq \frac{c+3}{2} - p$ . For every  $n > 2k > c$ ,  $d_{F,\alpha}(n) \geq 2^{\frac{n}{2}-k}$ .  $\square$

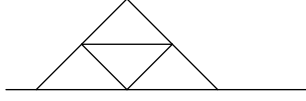


Figure 1:  $h_{\alpha_n, 2^{-n-p}} = \sum_{i=1}^4 h_{\beta_i, 2^{-n-p-1}}$

Let us illustrate the notion of relevant point on a few examples.

*Example 3.4.* Let  $F$  be the uniform norm. Every point is relevant, and  $\mathcal{R} = \mathcal{R}_0 = [0, 1]$ .

*Example 3.5.* Let  $F$  be the  $L^1$  norm. Every point is relevant, and  $\mathcal{R} = \mathcal{R}_1 = [0, 1]$ .

*Example 3.6.* Let  $F(f) = \sum_i 2^{-i} |f(q_i)|$ . Every  $q_i$  is relevant and  $\mathcal{R}_i$  contains  $\{q_0, \dots, q_{2^i}\}$ . Whether  $\mathcal{R}$  contains only the numbers  $q_i$  depends on the way they are distributed in the unit interval:

1. let us consider the *canonical enumeration of the dyadic rationals*, defined in the following way: for  $i = 2^n + k$  with  $0 \leq k < 2^n$ , let  $q_i = (2k + 1)2^{-n}$ . The important feature of this enumeration is that dyadic rationals are far from each other, in terms of their indices: if  $i < j$  then  $|q_i - q_j| \geq \frac{1}{j}$ . Indeed, let  $n$  be such that  $2^n \leq j < 2^{n+1}$ :  $|q_i - q_j| \geq 2^{-n} \geq \frac{1}{j}$ .

*Lemma 3.1.* *If  $(q_i)_{i \in \mathbb{N}}$  is the canonical enumeration of the dyadic rationals then  $\mathcal{R} = \mathbb{D}$ . Moreover if  $\alpha \notin \mathbb{D}$  then  $d_{F,\alpha}(n) \leq 2(n+1)$  for infinitely many  $n$ .*

*Proof.* Let  $\alpha \notin \mathbb{D}$  and  $n_0 \in \mathbb{N}$ . Assume  $d_{F,\alpha}(n) > 2(n+1)$  for all  $n \geq n_0$ .

First,  $F(h_{\alpha, \frac{1}{2^{n_0+1}}}) > 2^{-n_0}$  so there exists  $i \leq n_0$  such that  $|\alpha - q_i| < \frac{1}{2^{(n_0+1)}}$  otherwise the first  $n+1$  terms in the sum defining  $F$  are null and the norm is at most  $2^{-n}$ . Take  $i \leq n_0$  minimizing  $|\alpha - q_i|$ . As  $\alpha \neq q_i$  there exists  $n > n_0$  such that  $|\alpha - q_i| \geq \frac{1}{2^{(n+1)}}$ . Take  $n$  minimal. Again,  $F(h_{\alpha, \frac{1}{2^{(n+1)}}}) > 2^{-n}$  so there exists  $j \leq n$  such that  $|\alpha - q_j| < \frac{1}{2^{(n+1)}}$ . As  $|\alpha - q_j| < |\alpha - q_i|$ ,  $j > n_0 \geq i$ . Now,  $|q_i - q_j| \leq |\alpha - q_i| + |\alpha - q_j| < \frac{1}{2^n} + \frac{1}{2^{(n+1)}} < \frac{1}{n} \leq \frac{1}{j}$ , which gives a contradiction.  $\square$

More generally, and by the same argument, if  $f$  is non increasing and  $i < j$  implies  $|q_i - q_j| \geq f(j)$  then if  $\alpha \notin \mathbb{D}$ ,  $d_{F,\alpha}(n) \leq \frac{f(n+1)}{2}$  for infinitely many  $n$ . In particular if  $f(n) = o(2^{\frac{n}{2}})$  then  $\mathcal{R} = \mathbb{D}$ .

2. we now consider the case when the sequence  $(q_i)_{i \in \mathbb{N}}$  accumulates quickly at a point  $\alpha \notin \mathbb{D}$ , in which case  $\alpha$  may be relevant. For instance, if  $|q_{2^i} - \alpha| < 2^{-2^i}$  then one easily checks that  $d_{F,\alpha}(n) \geq 2^{\frac{n}{2}-2}$  for all  $n$ , so  $\alpha$  is relevant.

The terminology is justified by the next result: the value  $F(f)$  up to some precision (decreasing to 0 as  $k$  grows) only depends on the values of  $f$  on  $\mathcal{R}_k$ , so the points of  $\mathcal{R}_k$  are relevant to evaluate the norm of a function.

**Theorem 3.2.** *Let  $F$  be a norm that is weaker than the uniform norm. There exists a constant  $c$  such that if  $f \in \text{Lip}_1$  is null on  $\mathcal{R}_{2^k}$  then  $F(f) \leq c \cdot 2^{-k}$ .*

We first need a few lemmas.

**Lemma 3.2.** *For every  $\alpha \in [0, 1]$  and  $n \in \mathbb{N}$  there exists  $\beta$  such that  $|\alpha - \beta| \leq 1/(2d_{F,\alpha}(n))$  and  $d_\beta(n+2) \geq 2d_{F,\alpha}(n)$ .*

*Proof.* Let  $l < d_{F,\alpha}(n)$  and  $f \in \text{Lip}_1$  be supported on  $N(\alpha, 1/l)$  and  $F(f) > 2^{-n}$ . Let  $h_1, h_2$  be the maximal 1-Lipschitz functions supported on  $[0, \alpha]$  and  $[\alpha, 1]$  respectively. Let  $f_1 = \min(f, h_1)$ ,  $f_2 = \min(f, h_2)$  and  $f_3 = f_4 = (f - f_1 - f_2)/2$ . All  $f_i$  are 1-Lipschitz and are supported on  $N(\beta_i, 1/(2l))$

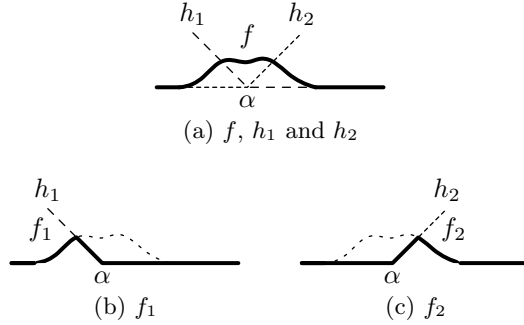


Figure 2:  $f = f_1 + f_2 + f_3 + f_4$

for some  $\beta_i \in \overline{N}(\alpha, 1/(2l))$ . As  $f = f_1 + f_2 + f_3 + f_4$  there exists  $i$  such that  $F(f_i) > 2^{-n-2}$ , which implies  $d_{\beta_i}(n+2) > 2l$ .

To each  $l < d_{F,\alpha}(n)$  is associated some  $\beta_l$ . By compactness of  $[0, 1]$ , there exists an accumulation point  $\beta$  when  $l$  tends to  $d_{F,\alpha}(n)$ . By continuity,  $\beta$  satisfies the conditions.  $\square$

**Lemma 3.3.** *For every  $\alpha \in [0, 1]$  and every  $n \in \mathbb{N}$  there exists  $\beta$  such that  $|\alpha - \beta| \leq 1/d_{F,\alpha}(n)$  and  $d_\beta(n+p) \geq 2^{\frac{p-3}{2}} d_{F,\alpha}(n)$  for all  $p \in \mathbb{N}$ .*

*Proof.* We iteratively apply Lemma 3.2. Let  $\beta_0 = \alpha$ . Given  $\beta_p$ , let  $\beta_{p+1}$  be obtained by applying Lemma 3.2 to  $\beta_p$  and  $n+2p$ . One has  $d_{\beta_p}(n+2p) \geq 2^p d_{F,\alpha}(n)$  and  $|\beta_p - \beta_{p+1}| \leq 2^{-p-1}/d_{F,\alpha}(n)$ .  $\beta_p$  is a Cauchy sequence,

let  $\beta$  be its limit. As  $|\beta - \beta_p| \leq 2^{-p}/d_{F,\alpha}(n)$ , a function supported on  $N(\beta_p, 2^{-p}/d_{F,\alpha}(n))$  is supported on  $N(\beta, 2^{-p+1}/d_{F,\alpha}(n))$  so  $d_\beta(n + 2p) \geq 2^{p-1}d_{F,\alpha}(n)$ . As  $d_\beta(n + 2p + 1) \geq d_\beta(n + 2p) \geq 2^{p-1}d_{F,\alpha}(n)$  we get the result.  $\square$

We will need the following refinement of Theorem 3.1.

**Lemma 3.4.** *There exists a constant  $c$  such that for all  $\epsilon$  and all  $f \in \text{Lip}_1$ , if  $|f| \leq \epsilon$  on  $R_{n,l}$  then  $F(f) \leq c\epsilon + l^2 2^{-n+6}$ .*

*Proof.* Let  $c$  be such that  $F \leq c\|\cdot\|_\infty$ . We decompose  $f$  into a sum  $f = g + h$  of 1-Lipschitz functions such that  $\|g\|_\infty \leq \epsilon$  and  $h = 0$  on  $R_{n,l}$ .  $g$  and  $h$  are defined as  $g(x) = f(x)$  if  $|f(x)| \leq \epsilon$ ,  $g(x) = -\epsilon$  if  $f(x) \leq -\epsilon$  and  $g(x) = \epsilon$  if  $f(x) \geq \epsilon$ , and  $h = f - g$ .

One easily checks that  $g$  and  $h$  are 1-Lipschitz. As  $f = g + h$ ,  $F(f) \leq F(g) + F(h)$  by triangular inequality.  $F(g) \leq c\epsilon$  and  $F(h) \leq l^2 2^{-n+6}$  by Theorem 3.1.  $\square$

*Proof of Theorem 3.2.* Lemma 3.3 gives

$$R_{2k,l} \subseteq N\left(\bigcap_{n \geq 2k} R_{n, 2^{\frac{n-3}{2}-k}l}, 1/l\right).$$

Assume  $l \geq 2^{\frac{3}{2}}$ . The set  $\bigcap_{n \geq 2k} R_{n, 2^{\frac{n-3}{2}-k}l}$  is contained in  $\mathcal{R}_k$ . Indeed, if  $n \geq 2k$  then  $l 2^{\frac{n-3}{2}-k} \geq 2^{\frac{n}{2}-k}$ .

As a result, if  $f \in \text{Lip}_1$  is null on  $\mathcal{R}_k$  then  $|f| \leq 1/l$  on  $R_{2k,l}$ , so by Lemma 3.4  $F(f) \leq \frac{c}{l} + l^2 2^{-2k+6}$  for some  $c$ . Now take  $l = 2^{\frac{k}{2}}$ :  $F(f) \leq c 2^{-\frac{k}{2}} + 2^{-k+6} \leq c' 2^{-\frac{k}{2}}$  for some  $c'$  that only depends on  $c$  (strictly speaking, the result is proved for  $k \geq 3$  as we need  $l \geq 2^{\frac{3}{2}}$ ). However, the result can be obtained for all  $k$  by changing the constant  $c'$ .  $\square$

The result can easily be generalized from the case of 1-Lipschitz functions to any  $f \in \mathcal{C}[0, 1]$ .

**Corollary 3.1.** *Let  $F$  be a norm that is weaker than the uniform norm. There exists  $c \in \mathbb{N}$  such that if  $f \in \mathcal{C}[0, 1]$  is null on  $\mathcal{R}_{2^{m_f(p)}}$  then  $F(f) \leq c \cdot 2^{-p}$ , where  $m_f$  is a modulus of continuity of  $f$ .*

*Proof.* Let  $c_0$  be such that  $F \leq c_0\|\cdot\|_\infty$ . Let  $L = 2^{m_f(p)-p+1}$ . Let  $k = m_f(p)$ . There exists an  $L$ -Lipschitz function  $g$  which is null on  $\mathcal{R}_{2^k}$  and such that  $\|f - g\|_\infty \leq 2^{-p}$ . Indeed, let  $p_i = i 2^{-m_f(p)}$  for  $i = 0$  to  $2^{m_f(p)}$ . Let  $g(p_i) = 0$  if  $d(p_i, \mathcal{R}_{2^k}) < 2^{-m_f(p)}$ ,  $g(p_i) = f(p_i)$  otherwise and extend  $g$  to a linear function between two consecutive points. One easily checks that  $g$  satisfies the required conditions.

First,  $F(f - g) \leq c_0 2^{-p}$ . Applying Theorem 3.2 to  $g/L$  gives  $F(g) \leq c_1 L 2^{-m_f(p)} \leq c_1 2^{-p}$  for some constant  $c_1$ , so  $F(f) \leq c_0 2^{-p} + c_1 2^{-p}$ .  $\square$

### 3.3 Complexity of norms

We now show how the complexity of a norm has an influence on the shape of the norm, which can be measured by the way it depends on the points and by the size of the set of relevant points. Precisely, our complexity measure will be the number of queries submitted to the oracle.

#### Query complexity

**Definition 3.4.** A *bounding class* is a class  $\mathcal{T}$  of functions  $t : \mathbb{N} \rightarrow \mathbb{N}$  satisfying the following conditions:

- $\mathcal{T}$  contains the constant function 1,
- $\mathcal{T}$  is closed downwards: if  $t' \leq t$  and  $t \in \mathcal{T}$  then  $t' \in \mathcal{T}$ ,
- $\mathcal{T}$  is stable under multiplication by a polynomial.

In particular  $\mathcal{T}$  contains all the (first-order) polynomials. The class POLY of functions that are bounded by polynomials is a bounding class. We say that a bounding class  $\mathcal{T}$  is *sub-exponential* if for every  $t \in \mathcal{T}$  and  $\epsilon > 0$ ,  $t = o(2^{\epsilon n})$ . The class POLY is an example of a sub-exponential bounding class.

Given an oracle Turing machine  $\mathcal{M}$  and  $n \in \mathbb{N}$ , run  $\mathcal{M}$  on input  $n$  and oracle  $(\text{id}, 0)$ , representing the null function with modulus  $m_0(p) = p$ .  $q$  is an *oracle query* if the machine eventually asks the oracle for the value of  $f_{\mathbb{D}}(q, p)$  for some  $p$ . Let  $Q_n$  be the set of oracle queries.

**Definition 3.5.** Let  $\mathcal{T}$  be a bounding class. A norm over  $\mathcal{C}[0, 1]$  has *query complexity* in  $\mathcal{T}$  if it is computable by a relativized oracle Turing machine for which the function  $n \mapsto |Q_n|$  belongs to  $\mathcal{T}$ .

A bound on the time complexity always induces a bound on the query complexity: if a norm  $\|\cdot\|$  is computable by a machine that on oracle  $\varphi$  and input  $n$ , halts in time  $t(|\varphi|, n)$ , then  $\|\cdot\|$  has query complexity  $t(\text{id}, n)$ . In particular, every polynomial-time computable norm has polynomial query complexity.

**Relating query complexity, dependence and relevant points** we are now able to relate the query complexity of a norm to the way it depends on points. The results are based on the following simple observation: if a norm  $F$  depends on a point then a machine computing  $F$  must query the oracle around that point.

**Lemma 3.5.** *The following equivalent statements hold for all  $\alpha, n$ :*

$$\begin{aligned} R_{n,l} &\subseteq \overline{N}(Q_{n+1}, 1/l) \\ \alpha &\in \overline{N}(Q_{n+1}, 1/d_{F,\alpha}(n)) \\ d_{F,\alpha}(n) &\leq 1/d(\alpha, Q_{n+1}). \end{aligned}$$

*Proof.* Let  $l = 1/d(\alpha, Q_{n+1})$ . If  $f \in \text{Lip}_1$  is supported on  $N(\alpha, 1/l)$  then  $f = 0$  on  $Q_{n+1}$  so  $F(f) < 2^{-n}$ . As a result,  $d_{F,\alpha}(n) \leq l$ .  $\square$

The notions of dependence and relevant points enable us to express formally the intuition that a polynomial-time computable norm cannot depend on a large set of points, as a machine computing it in polynomial-time only has little time to evaluate its input. It is more generally true of any norm that has low query complexity.

**Theorem 3.3.** *Let  $F$  be a norm and  $\mathcal{T}$  a bounding class. If  $F$  has query complexity in  $\mathcal{T}$  then for almost every  $\alpha$ ,  $d_{F,\alpha} \in \mathcal{T}$ .*

*In particular if  $\mathcal{T}$  is sub-exponential then the set of relevant points has Lebesgue measure 0.*

*Proof.* Let  $t \in \mathcal{T}$  be such that  $|Q_n| \leq t(n)$  for all  $n$ . Let  $U_i = \bigcup_n N(Q_n, \frac{1}{2t(n)(n+i+1)^2})$  and  $A_i = [0, 1] \setminus U_i$ . One has

$$\mu(U_i) \leq \sum_n \frac{1}{(n+i+1)^2} \leq \frac{1}{i}.$$

so  $\mu(A_i) \geq 1 - \frac{1}{i}$ . Let  $\alpha \in A_i$  and  $n \in \mathbb{N}$  : as  $\alpha \notin N(Q_n, \frac{1}{2t(n)(n+i+1)^2})$ ,  $d_{F,\alpha}(n) \leq 1/d(\alpha, Q_{n+1}) \leq 2t(n+1)(n+i+2)^2$  by Lemma 3.5. The function  $n \mapsto 2t(n+1)(n+i+2)^2$  belongs to  $\mathcal{T}$ .  $\square$

Moreover,

**Theorem 3.4.** *Let  $F$  be a norm and  $\mathcal{T}$  a sub-exponential bounding class. If  $F$  has query complexity in  $\mathcal{T}$  then the set of relevant points has Hausdorff dimension 0.*

*Proof.* We slightly refine the preceding proof. For  $s > 0$ , we replace the sets  $U_i$  by  $V_i^s = \bigcup_n N(Q_n, (t(n)(n+i)^2)^{-1/s})$ .

Again,  $\bigcap_i V_i^s$  contains all the relevant points as  $(t(n)(n+i)^2)^{1/s} = o(2^{\frac{n}{2}})$ , and its dimension is  $\leq s$ . As it is true for any  $s > 0$ , the set of relevant points has Hausdorff dimension 0.  $\square$

In particular, if  $F$  is polynomial-time computable then most of the points are irrelevant. In other words,  $F$  depends on a small set. As we show now, it is balanced by the fact that it highly depends on some points. We know from Proposition 3.4 that there exist points whose dependence function is at least of the order of  $2^{\frac{n}{2}}$  and the example of the  $L^1$  norm shows that the coefficient  $\frac{1}{2}$  cannot be increased in general. However for polynomial-time computable norms, the coefficient can be taken arbitrarily close to 1. First, one easily improves Proposition 3.3.

**Proposition 3.5.** *Let  $F$  be a norm and  $\mathcal{T}$  be bounding class. If  $F$  has query complexity in  $\mathcal{T}$  then  $\frac{2^n}{D_F(n)} \in \mathcal{T}$ .*

*Proof.* Let  $t \in \mathcal{T}$  be such that  $|Q_n| \leq t(n)$  for all  $n$ . Let  $l < F(1)2^n/(3t(n))$ . Let  $g = \frac{1}{t(n)} \sum_{q \in Q_n} h_{q,1/l}$ .  $g \in \text{Lip}_1$  and  $g = 1/(lt(n))$  on  $Q_n$  so  $F(1/(lt(n)) - g) \leq 2^{-n+1}$ , hence  $F(g) \geq F(1)/(lt(n)) - 2^{-n+1}$ . As a result there exists  $q \in Q_n$  such that  $F(h_{q,1/l}) \geq F(1)/(lt(n)) - 2^{-n+1} > 2^{-n}$ , so  $D_F(n) \geq d_{F,q}(n) \geq l$ . As it is true for any  $l < F(1)2^n/(3t(n))$ ,  $D_F(n) \geq F(1)2^n/(3t(n))$ .  $\square$

For instance if  $F$  has polynomial query complexity then  $D_F(n) \geq \frac{2^n}{P(n)}$  for some polynomial  $n$ . We raise the question whether this bound is reached: is there some  $\alpha$  such that  $\frac{2^n}{d_{F,\alpha}(n)} \in \mathcal{T}$ ? We leave the question open, but in the case when  $\mathcal{T}$  is the class of functions that are bounded by polynomials, we are able to prove that  $d_{F,\alpha}$  can be larger than  $2^{(1-\epsilon)n}$  for any  $\epsilon > 0$ . More precisely,

**Theorem 3.5.** *Let  $F$  be a polynomial-time computable norm. There exist  $\alpha \in [0, 1]$  and  $c > 0$  such that  $d_{F,\alpha}(n) \geq 2^{n-c\sqrt{n}\log n}$  for all sufficiently large  $n$ . The set of such  $\alpha$  is even dense.*

*Proof idea.* The idea is to start from some triangular function  $h_{\alpha_0,l}$  and to decompose it as a sum of many smaller triangular functions. As most of them will be far away from the query sets of the machine computing the norm, their norms will be very small. As the sum of the norms of all the small functions is bounded below by the norm of the initial function, one of the few functions,  $h_{\alpha_1,l'}$  that are close to the query set must have a large norm. Applying the same argument to the smaller function and iterating to infinity produces a sequence  $\alpha_i$  converging to some  $\alpha$  which will satisfy the conclusion of the theorem.  $\square$

We do not know whether this result can be improved: is the bound provided by Proposition 3.5 reached? In other words, is there  $\alpha$  such that  $d_{F,\alpha}(n) \geq \frac{2^n}{P(n)}$  for some polynomial  $P$  and all  $n$ ? Adapting the proof of Theorem 3.5 we are only able to prove the existence of  $\alpha$  such that  $d_{F,\alpha}(n) \geq \frac{2^n}{P(n)}$  for some polynomial  $P$  and *infinitely many*  $n$ .

We end this section by a characterization of the norms that have polynomial query complexity.

A compact set  $K \subseteq [0, 1]$  can be **polynomially covered** if for each  $n$  there exists a set  $A_n$  of cardinality bounded by a polynomial in  $n$  such that  $K \subseteq N(A_n, 2^{-n})$ .

**Proposition 3.6.** *A norm has polynomial query complexity if and only if for every  $k$ ,  $\mathcal{R}_k$  can be polynomially covered, where  $k$  is an argument of the polynomial.*

*Proof sketch.* If a norm has polynomial query complexity then by Lemma 3.5,  $\mathcal{R}_k \subseteq R_{2(n+k), 2^n} \subseteq \overline{N}(Q_{2(n+k)+1}, 2^{-n})$ . We then use the assumption that  $|Q_{2(n+k)+1}|$  is polynomial in  $n, k$ .



Conversely, assume that  $\mathcal{R}_k \subseteq N(A_{n,k}, 2^{-n})$  for some set  $A_{n,k}$  of cardinality bounded by  $P(n, k)$  for some polynomial  $P$ . We can assume w.l.o.g. that the points of  $A_{n,k}$  belong to  $\mathbb{D}_n$ . The additional oracle provides two types of information: given  $n, k$ , it provides the set  $A_{n,k}$  and given  $n, k, p$  and a list of  $|A_{n,k}|$  values, it provides a  $2^{-p}$ -approximation of  $\|f\|$  where  $f$  is the piecewise linear function with the corresponding values on  $A_{n,k}$ . We now describe the machine computing the norm. On input  $p$ , the machine asks for  $m_f(p)$ , then asks the auxiliary oracle for  $A_{m_f(p), 2m_f(p)}$ , evaluates  $f$  on the latter set at precision  $2^{-p}$  and then using the returned values, asks the auxiliary oracle for the norm of the corresponding piecewise linear function and outputs that value. Corollary 3.1 tells us that the output value is within  $c2^{-p}$  of the value norm of  $f$ , for some constant  $c$ . Taking  $c$  into account, the machine can be adjusted to compute the norm. It is routine to check that the oracle can be coded as an element of  $\{0, 1\}^{\mathbb{N}}$  and that the queries of the machines are polynomial in  $p$  and the size of the representation of  $f$ .  $\square$

## 4 One oracle access

In this section we investigate the extreme case of a functional whose “query complexity<sup>1</sup>” is bounded by 1, i.e. a functional  $F : \mathcal{C}[0, 1] \rightarrow \mathbb{R}$  that is computable by a machine making at most one oracle call on each precision input  $n$ . Technically, the representation of  $f$  contains two types of information: the modulus of continuity of  $f$  and the values of  $f$  on the dyadic rationals. Here we separate the representation of  $f$  into two oracles and restrict the machine to perform one query to the approximation oracle.

We are able to characterize exactly this class of functionals. While the result looks natural, the proof is more delicate than expected: it is what makes the result interesting. As the last result (Proposition 4.1) shows, the argument hides subtleties that make it non-uniform.

Observe that it is trivial to obtain a characterization of functionals  $F : (\mathbb{N} \rightarrow \mathbb{N}) \rightarrow (\mathbb{N} \rightarrow \mathbb{N})$  that are computable by an oracle Turing machine such that to compute  $F(f)(n)$ , does only one oracle call to  $f$ . Obviously, the functional  $F$  can be expressed as  $F(f)(n) = \varphi(f(\psi(n)))$  for some computable functions  $\varphi, \psi : \mathbb{N} \rightarrow \mathbb{N}$ . Indeed, let  $\varphi(m) = F(\lambda x.m)$  and  $\psi(n)$  be the question asked by the machine to the oracle on input  $n$ . If  $F$  is assumed to be polynomial-time computable, then so are  $\varphi$  and  $\psi$ . The argument is much more elaborate on the real numbers.

**Theorem 4.1.** *For a functional  $F : \mathcal{C}[0, 1] \rightarrow \mathbb{R}$  the following are equivalent:*

1.  *$F$  is computable by a (polynomial time) oracle Turing machine that does at most one query to the approximation oracle,*

---

<sup>1</sup>here we make informal use of this expression as the query complexity is only defined for norms.

2.  $F$  is of the form  $f \mapsto \phi(f(\alpha))$ , where  $\alpha$  is a (polynomial time) computable real number and  $\phi : \mathbb{R} \rightarrow \mathbb{R}$  is a (polynomial time) computable real function which is uniformly continuous and whose modulus of uniform continuity is bounded by a computable function (a polynomial).

Observe that  $\phi$  is uniquely determined by  $\phi(v) = F(\lambda x.v)$  where  $\lambda x.v$  is the constant function with value  $v$ . If  $F$  is not constant then  $\alpha$  can be proved to be unique.

One could imagine a kind of BSS model of oracle computation for functionals, where the machine is allowed to ask its oracle for the value  $f(\alpha)$ , giving  $\alpha$  in one step, and getting the value  $f(\alpha)$  in one step as well (see [BCSS98] for the usual BSS model). In such a model, it is obvious that a functional  $F$  computed by a machine making one oracle call should be of the form  $F(f) = \phi(f(\alpha))$ . Theorem 4.1 tells us that this is also true for oracle machines working at finite precision. Note however that the two models would not have the same computation power: the uniform norm would not be computable in such a model, as the machine should evaluate its input function on an infinite set (which, at finite precision, can be approximated by evaluating the function on a finite set).

## 4.1 Uniformity

Our question is now: can  $\alpha$  and  $\phi$  be efficiently computed from  $F$ ? As for  $\phi$ , the answer is positive: it can be easily recovered as  $\phi(v) = F(\lambda x.v)$ . However the proof of Theorem 4.1 is not fully uniform as the computation of  $\alpha$  relies on a modulus  $m$  and a  $k$  such that  $F$  varies by at least  $2^{-k}$  on  $\mathcal{C}_m[0,1]$ . These objects can be effectively found, but not necessarily efficiently. The next result shows that this problem cannot be got around.

**Proposition 4.1.** *There exist  $\alpha_k$  and  $\phi_k$  such that  $\alpha_k$  is not computable in polynomial time in  $k$  and  $\phi_k$  is not constant but  $F_k(f) := \phi_k(f(\alpha_k))$  is computable in time polynomial in  $k$ .*

As  $F_k$  is not constant, the decomposition  $(\alpha_k, \phi_k)$  of  $F_k$  is unique.

*Proof.* Let  $A \subseteq \mathbb{N}$  be such that the problem  $k \in A$  is decidable in time  $2^k$  but not in polynomial time. Let  $\alpha_k = 1$  if  $k \in A$ ,  $\alpha_k = 0$  if  $k \notin A$ . Let  $\phi_k(x) = 2^{-2^k} \cdot x$ . Let  $F_k(f) = \phi_k(f(\alpha_k))$ . First,  $\alpha_k$  is not polynomially computable in  $k$ .

Of course, each  $F_k$  is computable in polynomial time separately (for  $k$  is fixed and hence constant). Moreover, we prove that  $F_k$  is polynomial time computable, uniformly in  $k$ . In other words, there is an oracle Turing machine  $\mathcal{M}$  such that on oracle  $f$ ,  $\mathcal{M}^f(k, n)$  halts in time bounded above by a polynomial  $p(k, n)$  and outputs a rational  $r$  such that  $|F_k(f) - r| \leq 2^{-n}$ .

Intuitively, if  $f$  does not vary much then it can be evaluated at 0 so computing  $\alpha_k$  is not necessary; if  $f$  varies much then its modulus is large as

well as the size of the representation of  $f$ , which gives enough computation time for evaluating  $\alpha_k$ .

Given inputs  $(n, k)$ , the machine queries  $m_f(0)$  to the oracle and next:

- if  $n \leq 2^k - m_f(0) - 2$ , then query  $\psi_f(0, 0)$  and output an approximation of  $2^{-2^k} \psi_f(0, 0)$  with precision  $2^{-n-1}$ .
- if  $n \geq 2^k - m_f(0) - 1$  then decide  $k \in A$ , compute  $\alpha_k$  accordingly, query  $\psi_f(\alpha_k, n)$  and output  $2^{-2^k} \psi_f(\alpha_k, n)$ .

First observe that  $|f(\alpha_k) - f(0)| \leq |f(0) - f(1)| \leq 2^{m_f(0)}$ . If  $n \leq 2^k - m_f(0) - 2$ , then  $|\mathcal{M}^f(k, n) - F(f)| = |2^{-2^k} \psi_f(0, 0) - 2^{-2^k} f(\alpha_k)| = 2^{-2^k} |\psi_f(0, 0) - f(\alpha_k)| \leq 2^{-2^k} (|\psi_f(0, 0) - f(0)| + |f(0) - f(\alpha_k)|) \leq 2^{-2^k} (1 + 2^{m_f(0)}) \leq 2^{-2^k + m_f(0) + 1} \leq 2^{-n-1}$ . So the output value is a  $2^{-n}$ -approximation of  $F_k(f)$ . The computations are done in polynomial time.

If  $n \geq 2^k - m_f(0) - 1$  then the computation of  $\alpha_k$  runs in time  $\leq 2^k \leq n + m_f(0) + 1$  which is polynomial in  $n$  and  $m_f(0)$ . And it can be easily verified that  $2^{-2^k} \psi_f(\alpha_k, n)$  is a  $2^{-n}$ -approximation of  $F_k(f)$ .  $\square$

## 5 Summary and open questions

We have introduced the dependence function  $d_{F, \alpha}$  of a norm  $F$  on a point  $\alpha$  (Definition 3.1) and the notion of a relevant point (Definition 3.3).

The norm of a function is determined by the values of the function on the points of high dependence (Theorem 3.1). The set of relevant points is a growing union of compact sets  $\mathcal{R} = \bigcup_k \mathcal{R}_k$ .  $\mathcal{R}$  is always dense (Proposition 3.4) and the norm of a function at precision  $2^{-k}$  is determined by the value of the function on  $\mathcal{R}_{2^{m_f(k)}}$  (Theorem 3.2). Hence a machine computing the norm only has to evaluate its input function at the relevant points. Moreover, it has to: each relevant point must be close to some oracle query (Lemma 3.5).

We have shown the effects of query complexity restrictions on the norm, measured by the dependence function and the set of relevant points. In particular if a norm is computable in polynomial time then its set of relevant points has Hausdorff dimension 0 (Theorem 3.4), almost every point has a polynomial dependence function (Theorem 3.3) and there exist points of very high dependence (Theorem 3.5). We also get a characterization of norms with polynomial query complexity (Proposition 3.6).

We characterize the functionals  $F : \mathcal{C}[0, 1] \rightarrow \mathbb{R}$  that are computable by a Turing machine allowed to make at most one oracle query on each input (Theorem 4.1). We show that the characterization is not fully uniform in terms of complexity (Proposition 4.1).

## 5.1 Open questions

Is it possible to obtain a nice characterization of the functionals  $F : \mathcal{C}[0, 1] \rightarrow \mathbb{R}$  that are polynomial-time computable relative to some oracle, i.e. to extend Proposition 3.6 to the general case? More generally is it possible to extend our analysis from norms to general functionals over  $\mathcal{C}[0, 1]$ ? The dependence of a functional on a point should be local, i.e. depend on the argument  $f \in \mathcal{C}[0, 1]$  of the functional: the functional  $F(f) = f(f(0))$  intuitively depends on 0 and  $f(0)$ .

Our analysis is relevant when considering deterministic time complexity classes. What about the non-deterministic case? The uniform norm is non-deterministically polynomial-time computable, contrary to the  $L^1$  norm, but they have the same sets of relevant points. What about space complexity?

## Acknowledgments

The authors wish to thank Emmanuel Hainry, Emmanuel Jeandel and Romain Péchoux for fruitful discussions on the subject.

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## A Proof of Theorem 3.1

The proof intuitively works as follows: if  $f$  is null on  $R_{n,l}$  then it is supported on points of low dependence.  $f$  can then be decomposed as a sum of functions supported on small neighborhoods of points of low dependence. The norm of each small function being small, the norm of their sum will also be small.

We actually prove that if  $f$  is moreover nonnegative then  $F(f) \leq l^2 2^{-n+5}$ . It gives the result for general  $f$  by decomposing  $f = f^+ - f^-$  where  $f^+$  and  $f^-$  are nonnegative.

**Lemma A.1.** *Let  $\alpha \in [0, 1]$  and  $g \in \text{Lip}_1$ . If  $\text{Supp}(g)$  is disjoint from  $R_{n,l}$  and contained in  $N(\alpha, 1/l)$  then  $F(g) \leq 2^{-n+1}$ .*

*Proof.* If  $d_{F,\alpha}(n) \leq l$  then  $F(g) \leq 2^{-n}$ . Otherwise,  $g(\alpha) = 0$  and we decompose  $g$  into the sum of two 1-Lipschitz functions  $g_0, g_1$  supported on  $(\alpha - 1/l, \alpha)$  and  $(\alpha, \alpha + 1/l)$  respectively. For each  $i \in \{0, 1\}$ , either  $g_i = 0$  or there exists  $\beta \in \text{Supp}(g_i)$ . In the latter case,  $g_i$  is supported on  $N(\beta, 1/l)$  and  $d_{F,\beta}(n) < l$  so  $F(g_i) \leq 2^{-n}$ . As a result,  $F(g) \leq F(g_0) + F(g_1) \leq 2^{-n+1}$ .  $\square$

*Proof of Theorem 3.1.* If  $l \leq 1$  then  $R_{n,l} = [0, 1]$  so  $F(f) = 0$ . We assume now that  $l > 1$ . Let  $A = \{\frac{2k}{l} : k \in \mathbb{N}, k \leq \frac{l}{2}\}$  and  $B = \{\frac{2k+1}{l} : k \in \mathbb{N}, k \leq \frac{l-1}{2}\}$ . Let  $d_A(x) = d(x, A)$  and  $d_B(x) = d(x, B)$ . Observe that  $d_A + d_B = \frac{1}{l}$ .

Let  $f \in \text{Lip}_1$  be nonnegative. Define for  $n, i \geq 0$  the following functions, depicted in Figure 3:

$$\begin{aligned} g_{2n} &= \min\left(\frac{2n}{l} + d_A, f\right), & f_0 &= g_0, \\ g_{2n+1} &= \min\left(\frac{2n+1}{l} + d_B, f\right), & f_{i+1} &= g_{i+1} - g_i. \end{aligned}$$

For all  $i \geq 0$ ,  $g_i$  is 1-Lipschitz, so  $f_0$  is 1-Lipschitz and  $f_{i+1}$  is 2-Lipschitz.

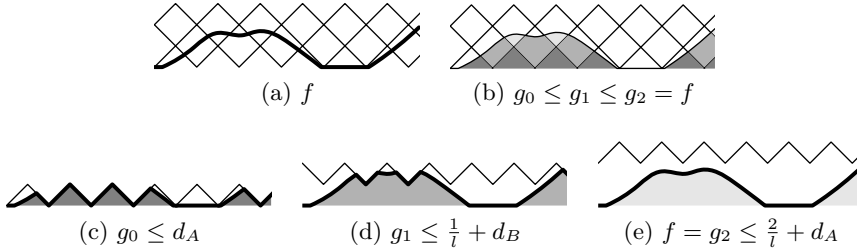


Figure 3: The functions  $g_i$

One has  $g_{2n} \leq g_{2n+1} \leq g_{2n} + 2d_B$  and  $g_{2n+1} \leq g_{2n+2} \leq g_{2n+1} + 2d_A$  so  $0 \leq f_{2n+1} \leq 2d_B$  and  $0 \leq f_{2n+2} \leq 2d_A$ . In particular,  $f_{2n+1} = 0$  on  $B$  and  $f_{2n} = 0$  on  $A$ .

Assume that  $\text{Supp}(f)$  is disjoint from  $R_{n,l}$ . As  $l \leq D_F(n)$ ,  $R_{n,l} \neq \emptyset$  so  $f$  vanishes at some point. As  $f$  is 1-Lipschitz,  $\|f\|_\infty \leq 1$  so  $f_k = 0$  for all  $k \geq l+1$ : indeed,  $g_k = g_{k-1} = f$ .

For each  $i$ ,  $\text{Supp}(f_i) \subseteq \text{Supp}(f)$  is also disjoint from  $R_{n,l}$ . As  $f_i$  is null on  $A$  or  $B$ ,  $\frac{f_i}{2}$  is the sum of at most  $\frac{l+3}{2}$  functions  $g$  satisfying the conditions of Lemma A.1 so  $F(f_i) \leq (l+3)2^{-n+1}$ . As  $f = f_0 + \dots + f_k$  with  $k = \lceil l+1 \rceil - 1 < l+1$ ,  $F(f) \leq (l+2)(l+3)2^{-n+1} \leq l^2 2^{-n+5}$  as  $l \geq 1$ .  $\square$

## B Proof of Theorem 3.5

**Lemma B.1.** *Let  $k, p, n \in \mathbb{N}$  and  $\alpha \in [2^{-k}, 1 - 2^{-k}]$ . There exists  $\beta \in N(\alpha, 2^{-k})$  such that*

$$F(h_{\beta, 2^{-p-k}}) \geq \frac{1}{P(n)} (2^{-p-1} F(h_{\alpha, 2^{-k}}) - 2^{p-n+1}).$$

*Proof.* We decompose  $h_{\alpha, 2^{-k}}$  as a sum of  $2^{2p}$  functions  $h_{\beta_i, 2^{-p-k}}$ ,  $i = 1 \dots, 2^{2p}$  where  $\beta_i$  ranges over the set  $B = \{\alpha \pm j2^{-p-k} : 0 \leq j < 2^p\}$  of cardinality  $2^{p+1} - 1$  (see Figure 4). Each  $\beta$  is the center of at most  $2^p$  functions, so

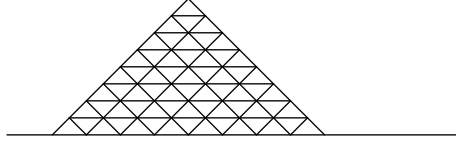


Figure 4:  $h_{\alpha, 2^{-k}} = \sum_{i=1}^{2^{2p}} h_{\beta_i, 2^{-p-k}}$ . Here,  $p = 3$ .

$$F(h_{\alpha, 2^{-k}}) \leq 2^p \sum_{\beta \in B} F(h_{\beta, 2^{-p-k}}).$$

We split  $B$  into a disjoint union  $B_0 \cup B_1$ :  $\beta \in B_0$  iff  $d(\beta, Q_n) < 2^{-p-k}$ . First,  $|B_0| \leq 2|Q_n|$ . Indeed, to each  $\beta \in B_0$  one can associate some  $q \in Q_n$  such that  $|\beta - q| < 2^{-p-k}$ . This mapping is two-to-one so  $|B_0| \leq 2|Q_n|$ .

Let  $M = \max_{\beta \in B_0} F(h_{\beta, 2^{-p-k}})$ . Observe that  $M = 0$  if  $B_0 = \emptyset$ . If  $\beta \in B_1$  then  $F(h_{\beta, 2^{-p-k}}) \leq 2^{-n+1}$ , so

$$\begin{aligned} F(h_{\alpha, 2^{-k}}) &\leq 2^p \sum_{\beta \in B_0} F(h_{\beta, 2^{-p-k}}) + 2^p \sum_{\beta \in B_1} F(h_{\beta, 2^{-p-k}}) \\ &\leq 2^p |B_0| M + 2^{p-n+1} |B_1| \\ &\leq 2^{p+1} P(n) M + 2^{2p-n+2}. \end{aligned}$$

As a result,

$$M \geq \frac{1}{P(n)} (2^{-p-1} F(h_{\alpha, 2^{-k}}) - 2^{p-n+1}).$$

If the term on the right-hand side is positive then  $M$  is positive so  $B_0 \neq \emptyset$  and  $M = F(h_{\beta, 2^{-p-k}})$  for some  $\beta \in B_0$ . If the right-hand side is nonpositive then every  $\beta$  satisfies the required condition.  $\square$

*Claim B.1.* There exist  $k_0$  and  $d$  such that for all  $k \geq k_0$  and  $p = \lceil d\sqrt{k} \log(k) \rceil$ ,

$$\frac{2^{-p-2-k-\sqrt{k}}}{P(2p+4+k+\sqrt{k})} > 2^{-(p+k)-\sqrt{p+k}}.$$

*Proof.* We look for  $p$  satisfying  $\sqrt{p+k} - \sqrt{k} > 2 + \log P(2p+4+k+\sqrt{k})$ . Let  $d_0$  be the degree of  $P$  and  $d > 2d_0$ . Let  $p = \lceil \sqrt{k} \log k \rceil \in o(k)$ .

$\sqrt{p+k} - \sqrt{k} \sim \frac{p}{2\sqrt{k}} \geq d \log k / 2$  and  $2 + \log P(2p+4+k+\sqrt{k}) \sim d_0 \log k$  so the inequality is satisfied for all sufficiently large  $k$ .  $\square$

**Lemma B.2.** *If  $F(h_{\alpha, 2^{-k}}) > 2^{-k-\sqrt{k}}$  then there exists  $\beta \in N(\alpha, 2^{-k})$  such that  $F(h_{\beta, 2^{-p-k}}) > 2^{-p-k-\sqrt{p+k}}$  where  $p = \lceil \sqrt{k} \log k \rceil$ .*

*Proof.* Let  $p \in \mathbb{N}$  and  $n = \lceil 2p + 3 + k + \sqrt{k} \rceil$ . Applying Lemma B.1 gives  $\beta \in N(\alpha, 2^{-k})$  such that

$$F(h_{\beta, 2^{-p-k}}) \geq \frac{2^{-p-2-k-\sqrt{k}}}{P(2p+4+k+\sqrt{k})}.$$

When  $p$  tends to infinity, the right-hand side eventually exceeds  $2^{-(p+k)-\sqrt{p+k}}$ . Actually, it happens early.

As a result,  $F(h_{\beta, 2^{-p-k}}) > 2^{-(p+k)-\sqrt{p+k}}$  for  $p = \lceil d\sqrt{k} \log k \rceil$ , if  $k \geq k_0$ .  $\square$

*Proof of Theorem 3.5.* Observe that if the result holds for a norm  $F' = NF$  with  $N \in \mathbb{N}$  then the result holds for  $F$ .

Lemma B.2 provides  $d$  and  $k_0$ . We define by induction  $\alpha_i, p_i, k_i$ . We start from  $k_0, \alpha_0 \in [2^{-k_0}, 1 - 2^{-k_0}]$  and we assume that  $F(h_{\alpha_0, 2^{-k_0}}) > 2^{-\lambda k_0}$ , multiplying  $F$  by a constant if necessary. Applying Lemma B.2 to  $\alpha_i$  and  $k_i$  gives  $\beta$ . Let  $p_i = \lceil d\sqrt{k_i} \log(k_i) \rceil$ ,  $\alpha_{i+1} = \beta$  and  $k_{i+1} = k_i + p_i$ . One has  $F(h_{\alpha_i, 2^{-k_i}}) > 2^{-k_i-\sqrt{k_i}}$  and  $|\alpha_i - \alpha_{i+1}| < 2^{-k_i}$  for all  $i$ .

As  $k_i$  is increasing,  $\alpha_i$  is a Cauchy sequence so it converges to some  $\alpha$ . One has  $|\alpha_i - \alpha| \leq 2^{-k_i+1}$ .

Let  $n_i = \lceil k_i + \sqrt{k_i} \rceil$  for some  $i$ .  $h_{\alpha_i, 2^{-k_i}}$  is supported on  $N(\alpha, 2^{-k_i+2})$  and  $F(h_{\alpha_i, 2^{-k_i}}) > 2^{-k_i-\sqrt{k_i}} \geq 2^{-n_i}$  so  $d_{F, \alpha}(n_i) \geq 2^{k_i-2}$ .

One has  $n_{i+1} - k_i \sim k_{i+1} - k_i \sim d\sqrt{k_i} \log k_i$ , so if  $i$  is sufficiently large then  $n_{i+1} - k_i \leq (d+1)\sqrt{k_i} \log k_i \leq (d+1)\sqrt{n_i} \log(n_i)$ .

Now given  $n \in \mathbb{N}$ , let  $i$  be such that  $n_i \leq n < n_{i+1}$ . If  $i$  is sufficiently large then  $k_i \geq n - (d+1)\sqrt{n} \log n$  so  $d_{F, \alpha}(n) \geq d_{F, \alpha}(n_i) \geq 2^{k_i-2} \geq 2^{n-(d+1)\sqrt{n} \log n - 2}$ .

As a result, for all sufficiently large  $n$ ,  $d_{F, \alpha}(n) \geq 2^{n-(d+2)\sqrt{n} \log n}$ .  $\square$



## C Proof of Theorem 4.1

*Notation C.1.* Assume a function  $m: \mathbb{N} \rightarrow \mathbb{N}$ . Let  $\mathcal{C}_m[0, 1]$  denote the set of continuous functions defined over the interval  $[0, 1]$  having a modulus of continuity  $m$ .

We prove  $1 \Rightarrow 2$ , the other direction is straightforward. Let  $\mathcal{M}$  be an oracle Turing machine computing  $F$  and such that on each input  $n$  the machine does at most one oracle call to the approximation oracle. We have two cases.

*Case 1.* Assume  $F$  is constant. That is  $F(f) = a$  for some  $a \in \mathbb{R}$ . Let  $\phi(y) = a$  and  $\alpha = 0$  for instance. Obviously,  $F$  is (polynomial-time) computable if and only if  $\phi$  is (polynomial-time) computable.

*Case 2.* Assume  $F$  is not constant. We first define  $\phi(y) = F(g_y)$  where  $g_y$  is the constant function with value  $y$ .

Let  $f_0, g_0$  and  $n_0$  be such that  $|F(f_0) - F(g_0)| > 2^{-n_0+1}$ . Let  $m$  be a common modulus of continuity for  $f_0$  and  $g_0$ . We can assume w.l.o.g. that  $m(p) \geq p$  and  $m$  is nondecreasing, replacing  $m(p)$  with  $\max(m(0), m(1), \dots, m(p), p)$  if necessary. Let  $M(p) = m(p+1)$ .  $M \geq m$  is also a modulus for  $f_0$  and  $g_0$ .

When the machine computing  $F$  is run on oracle  $(M, \psi)$  and input  $n \geq n_0$  for some approximation function  $\psi$ , the machine must consult  $\psi$ . Indeed, otherwise it cannot distinguish between  $f_0$  and  $g_0$ , which implies  $|F(f_0) - F(g_0)| \leq 2^{-n+1} \leq 2^{-n_0+1}$  contradicting the assumption. For every  $n \geq n_0$ , let  $(q_n, p_n)$  be the query submitted by  $\mathcal{M}^{(M, \psi)}(n)$  to  $\psi$  ( $(q_n, p_n)$  does not depend on  $\psi$ , as the machine is deterministic does not have consulted it yet).

*Claim C.1.*  $\phi$  is uniformly continuous and  $n \mapsto p_{n+1}$  is a modulus of uniform continuity for  $\phi$ .

*Proof.* Assume  $|x - y| \leq 2^{-p_{n+1}}$ . Let  $r$  be a rational number such that  $|x - r| < 2^{-p_{n+1}}$  and  $|y - r| < 2^{-p_{n+1}}$ . When evaluating  $F(g_x)$  and  $F(g_y)$  at precision  $2^{-n-1}$ , the oracle can answer  $r$  to the query  $(q_{n+1}, p_{n+1})$ . The deterministic machine will produce the same output, so  $|F(g_x) - F(g_y)| \leq 2^{-n}$ , hence  $|\phi(x) - \phi(y)| \leq 2^{-n}$ .  $\square$

Observe that the modulus of uniform continuity of  $\phi$  is computable. In case the machine runs in polynomial time, the modulus is bounded by a polynomial.

We now define  $\alpha$ .

*Claim C.2.* Assume  $\alpha$  is an accumulation point of the sequence  $(q_n)_{n \in \mathbb{N}}$ . Then

1. Let  $f, g \in \mathcal{C}_M[0, 1]$ : if  $f = g$  on a neighborhood of  $\alpha$  then  $F(f) = F(g)$ .
2. Let  $f, g \in \mathcal{C}_m[0, 1]$ : if  $f(\alpha) = g(\alpha)$  then  $F(f) = F(g)$ .

*Proof.* 1) Assume  $f = g$  on a neighborhood  $U$  of  $\alpha$  where  $f, g \in \mathcal{C}_M[0, 1]$ . Both functions  $f$  and  $g$  have representations  $\psi_f$  and  $\psi_g$  such that  $\psi_f(q, p) = \psi_g(q, p)$  for every  $q \in U \cap \mathbb{Q}$  and  $p \in \mathbb{N}$ . Since  $\alpha$  is an accumulation point of  $(q_n)_{n \in \mathbb{N}}$ , there exists an infinite set  $E \subseteq \mathbb{N}$  such that for all  $k \in E$  we have  $q_k \in U$ . Given the representations  $\psi_f$  and  $\psi_g$ , the machine cannot distinguish between  $f$  and  $g$  for input precisions  $k \in E$ , that is  $\mathcal{M}^{M, \psi_f}(k) = \mathcal{M}^{M, \psi_g}(k) = r_k$  for every  $k \in E$ . We have  $|r_k - F(f)| \leq 2^{-k}$  and  $|r_k - F(g)| \leq 2^{-k}$ , so  $|F(f) - F(g)| \leq 2^{-k+1}$ . Given that  $E$  is infinite we have the desired result  $F(f) = F(g)$ . This proves the first part of the claim.

2) Now assume  $f(\alpha) = g(\alpha)$  with  $f, g \in \mathcal{C}_m[0, 1]$ . There exists a function  $g_n$  such that: (1)  $g_n$  coincides with  $f$  on  $N(\alpha, 2^{-n})$ , (2)  $\|g - g_n\|_\infty \leq 2^{-n+1}$  and (3)  $M$  is a modulus for  $g_n$  ( $g_n$  cannot have modulus  $m$  in general, this is why we need to consider  $M$ ).  $g_n$  can be constructed as follows.

Let  $\beta_n = \max(\alpha - 2^{-n}, 0)$  and  $\gamma_n = \min(\alpha + 2^{-n}, 1)$ . Let  $\delta_1 = f(\beta_n) - g(\beta_n)$  and  $\delta_2 = f(\gamma_n) - g(\gamma_n)$ . We have  $|\delta_1| \leq |f(\beta_n) - f(\alpha)| + |f(\alpha) - g(\alpha)| + |g(\alpha) - g(\beta_n)| \leq |\beta_n - \alpha| + 0 + |\beta_n - \alpha| \leq 2^{-n+1}$ . Similarly,  $|\delta_2| \leq 2^{-n+1}$ .

Now define  $g_n: [0, 1] \rightarrow \mathbb{R}$  as follows. For  $\beta_n \leq x \leq \gamma_n$ :  $g_n(x) = f(x)$ . For  $x \leq \beta_n$ :  $g_n(x) = g(x) + \delta_1$ . For  $x \geq \gamma_n$ :  $g_n(x) = g(x) + \delta_2$ . It can be easily verified that  $g_n$  satisfies the required properties. We have  $f = g_n$  on a neighborhood of  $\alpha$ , so from Part (1) of the Claim we have  $F(f) = F(g_n)$ . As  $F$  is continuous and  $g_n$  converge to  $g$  in the uniform norm,  $F(g_n)$  converge to  $F(g)$  so  $F(f) = F(g)$ . This completes the proof of Claim C.2.  $\square$

*Claim C.3.* If  $(q_n)_{n \in \mathbb{N}}$  has more than one accumulation point, then  $F$  is constant on  $\mathcal{C}_m[0, 1]$ .

*Proof.* Assume that  $(q_n)_{n \in \mathbb{N}}$  has two different accumulation points  $\alpha$  and  $\beta$ . Let  $f, g \in \mathcal{C}_m[0, 1]$  be arbitrary. We will show that  $F(f) = F(g)$ , hence  $F$  is constant. We consider two cases. First, assume  $|g(\beta) - f(\alpha)| \leq |\beta - \alpha|$ . Let  $h$  be the linear function such that  $h(\alpha) = f(\alpha)$  and  $h(\beta) = g(\beta)$ . By the current assumption,  $h \in \text{Lip}_1[0, 1] \subseteq \mathcal{C}_m[0, 1]$  as  $m(p) \geq p$  so by Claim C.2 we have  $F(f) = F(h) = F(g)$ .

Next consider the case  $|g(\beta) - f(\alpha)| > |\beta - \alpha|$ . Without loss of generality assume that  $f(\alpha) > g(\beta)$ . One can find  $h_1, \dots, h_{2k+2} \in \text{Lip}_1[0, 1]$  such that, letting  $h_0 = g$  and  $h_{2k+2} = f$ ,  $h_{2i+1}(\beta) = h_{2i}(\beta)$  and  $h_{2i+2}(\alpha) = h_{2i+1}(\alpha)$ ,  $i = 0, \dots, k$ . From Claim C.2,  $F(g) = F(h_1) = \dots = F(h_{2k+2}) = F(f)$ .  $\square$

As  $F$  is not constant by assumption, the sequence  $(q_n)_{n \in \mathbb{N}}$  has a unique accumulation point  $\alpha$ . Recall the function  $\phi(y) = F(g_y)$  where  $g_y$  is the constant function with value  $y$ . By Claim C.2,  $F(f) = \phi(f(\alpha))$  for all  $f \in \mathcal{C}_m[0, 1]$ , as  $f$  coincides with  $g_{f(\alpha)}$  at  $\alpha$ .

*Claim C.4.*  $\phi$  is uniformly continuous and  $n \mapsto p_{n+1}$  is a modulus of uniform continuity for  $\phi$ .

*Proof.* Assume  $|x - y| \leq 2^{-p_{n+1}}$ . Let  $r$  be a rational number such that  $|x - r| < 2^{-p_{n+1}}$  and  $|y - r| < 2^{-p_{n+1}}$ . When evaluating  $F(g_x)$  and  $F(g_y)$  at precision  $2^{-n-1}$ , the oracle can answer  $r$  to the query  $(q_{n+1}, p_{n+1})$ . The deterministic machine will produce the same output, so  $|F(g_x) - F(g_y)| \leq 2^{-n}$ , hence  $|\phi(x) - \phi(y)| \leq 2^{-n}$ .  $\square$

Observe that the modulus of uniform continuity of  $\phi$  is computable. In case the machine runs in polynomial time, the modulus is bounded by a polynomial.

In order to prove that  $\alpha$  is (polytime) computable, we first show that the speed of convergence of  $(q_n)_{n \in \mathbb{N}}$  to  $\alpha$  is also a modulus of continuity for  $\phi$ .

*Claim C.5.* The function  $n \mapsto -\log_2 |\alpha - q_{n+1}| - 1$  is a modulus of uniform continuity for  $\phi$ . In other words,  $|x - y| \leq 2^{|\alpha - q_{n+1}|}$  implies  $|\phi(x) - \phi(y)| \leq 2^{-n}$ .

*Proof.* Let  $n \in \mathbb{N}$ . Assume  $x, y \in \mathbb{R}$  such that  $|x - y| \leq 2^{-(-\log_2 |\alpha - q_{n+1}| - 1)} = 2^{|\alpha - q_{n+1}|}$ . Then let  $f, g$  be the affine functions satisfying  $f(\alpha) = x$ ,  $g(\alpha) = y$ , and  $f(q_{n+1}) = g(q_{n+1}) = \frac{x+y}{2}$ . As  $|x - y| \leq 2^{|\alpha - q_{n+1}|}$ ,  $f, g \in \text{Lip}_1[0, 1] \subseteq \mathcal{C}_m[0, 1]$ . Then  $f$  and  $g$  have representations  $\psi_f$  and  $\psi_g$  that give the same answer for the query  $(q_{n+1}, p_{n+1})$ . Hence,  $\mathcal{M}^{M, \psi_f}(n+1) = \mathcal{M}^{M, \psi_g}(n+1)$ . Thus we have  $|F(f) - F(g)| \leq 2^{-n}$ . Therefore,  $|\phi(x) - \phi(y)| = |\phi(f(\alpha)) - \phi(g(\alpha))| = |F(f) - F(g)| \leq 2^{-n}$ . This completes the proof of the Claim.  $\square$

As  $\phi$  is not constant, its modulus cannot be sub-linear, so  $q_n$  must converge quickly to  $\alpha$ .

*Claim C.6.* There exists  $k \in \mathbb{N}$  such that for all  $n \in \mathbb{N}$  the following holds:  $|\alpha - q_n| \leq 2^{k-n}$ .

*Proof.* By assumption  $F$  is not constant, so  $\phi$  is not constant. As we show now, it implies that its modulus must be at least linear, i.e.  $m(n) \geq n - k$  for some  $k$  and all sufficiently large  $n$ .

Let  $a < b$  be such that  $\phi(a) \neq \phi(b)$ . Let  $k \in \mathbb{N}$  be such that  $|\phi(a) - \phi(b)| \geq 2^{-k}(b-a)$ . Let  $m$  be a modulus of uniform continuity of  $\phi$ . Let  $n$  be such that  $|\phi(a) - \phi(b)| > 2^{-n}$ : one must have  $b - a \geq 2^{-m(n)}$ . We divide the interval  $[a, b]$  into intervals of length  $\leq 2^{-m(n)}$ . We can take  $p = \lfloor (b-a)2^{m(n)} \rfloor \geq 1$  subintervals. As  $\phi$  does not vary more than  $2^{-n}$  on each subinterval, a repeated use of the triangular inequality gives  $|\phi(a) - \phi(b)| \leq p2^{-n} \leq (b-a)2^{m(n)-n}$  so  $m(n) \geq n - k$ .

As  $m(n) = -\log_2 |\alpha - q_{n+1}| - 1$  is a modulus of  $\phi$ , one has  $|\alpha - q_{n+1}| \leq 2^{k-n-1}$ . This completes the proof of the Claim.  $\square$

To summarize, for every  $f \in \mathcal{C}_m[0, 1]$ ,  $F(f) = \phi(f(\alpha))$ . Observe that the construction of  $\alpha$  may depend on  $m$ . We show that it does not.

Let  $m'$  be a nondecreasing function satisfying  $m'(p) \geq p$  and such that  $F$  is not constant on  $\mathcal{C}_{m'}[0, 1]$ . The argument developed so far associates to  $m'$  a real number  $\alpha' \in [0, 1]$  such that  $F(f) = \phi(f(\alpha'))$  for all  $f \in \mathcal{C}_{m'}[0, 1]$ .

*Claim C.7.*  $\alpha' = \alpha$ .

*Proof.* Assume  $\alpha' \neq \alpha$ . As  $\phi$  is not constant there exist  $a, b$  such that  $\phi(a) \neq \phi(b)$ .  $a$  and  $b$  can be chosen arbitrarily close to each other: we can assume without loss of generality that  $|a - b| \leq |\alpha - \alpha'|$ . Let  $f$  be the affine function satisfying  $f(\alpha) = a$  and  $f(\alpha') = b$ . Then  $f$  is in  $\text{Lip}_1[0, 1] \subseteq \mathcal{C}_m[0, 1] \cap \mathcal{C}_{m'}[0, 1]$ . As a result,  $\phi(f(\alpha)) = F(f) = \phi(f(\alpha'))$  which implies  $\phi(a) = \phi(b)$ : we get a contradiction.  $\square$

As a result, for every  $f \in \mathcal{C}[0, 1]$ ,  $F(f) = \phi(f(\alpha))$ . Indeed,  $f$  has a modulus  $m' \geq m$  so  $F(f) = \phi(f(\alpha')) = \phi(f(\alpha))$ .

Now, to compute  $\alpha$ , we need a modulus  $m$  such that  $F$  is not constant on  $\mathcal{C}_m[0, 1]$ . The point is that  $m$  can be assumed to be  $m(n) = n + k$  for some  $k$ . Indeed, as  $F$  is not constant and the Lipschitz functions are dense in  $\mathcal{C}[0, 1]$ , there exist two such Lipschitz functions  $f_0$  and  $g_0$  such that  $F(f_0) \neq F(g_0)$ . If  $2^k$  bounds the Lipschitz constants of  $f_0$  and  $g_0$  then  $m(n) = n + k$  is a common modulus for  $f_0$  and  $g_0$  so  $F$  is not constant on  $\mathcal{C}_m[0, 1]$ . From this  $m$ , the sequence  $q_n$  can be computed (in polynomial time) so  $\alpha$  can be computed (in polynomial time) thanks to Claim C.6.

This completes the proof of the theorem.