Under Physics-Motivated Constraints, Generally-Non-Algorithmic Computational Problems Become Algorithmically Solvable

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1. Physically Meaningful Computations with Real Numbers: a Brief Reminder

- In practice, many quantities such as weight, speed, etc., are characterized by real numbers.
- To get information about the corresponding value x, we perform a measurement, and get a value $\widetilde{x}$.
- Measurements are never absolute accurate.
- We usually also know the upper bound Δ on the the measurement error $\Delta x \stackrel{\text{def}}{=} \widetilde{x} - x$: $|x - \widetilde{x}| \le \Delta$.
- To fully characterize a value x, we must measure it with a higher and higher accuracy, e.g., 2^{-n} with $n = 0, 1, \ldots$
- So, we get a sequence of rational numbers r_n for which $|x - r_n| \le 2^{-n}$.
- Such sequences represent real numbers in computable analysis.

2. Known Negative Results

- No algorithm is possible that, given two numbers x and y, would check whether $x = y$.
- Similarly, we can define a computable function $f(x)$ from real numbers to real numbers as a mapping that:
  - given an integer n, a rational number x_m and its accuracy 2^{-m},
  - produces y_n which is 2^{-n}-close to all values $f(x)$ with $d(x, x_m) \leq 2^{-m}$ (or nothing)

  so that for every x and for each desired accuracy n, there is an m for which a y_n is produced.
- We can similarly define a computable function $f(x)$ on a computable compact set K.
- No algorithm is possible that, given f, returns x s.t. $f(x) = \max\limits_{y \in K} f(y)$. (The max itself *is* computable.)

3. From the Physicists' Viewpoint, These Negative Results Seem Rather Theoretical

- In mathematics, if two numbers coincide up to 13 digits, they may still turn to be different.
- For example, they may be 1 and $1 + 10^{-100}$.
- In physics, if two quantities coincide up to a very high accuracy, it is a good indication that they are equal:
  - if an experimentally value is very close to the theoretical prediction,
  - this means that this theory is (triumphantly) true.
- This is how General Relativity was confirmed.
- This is how physicists realized that light is formed of electromagnetic waves: their speeds are very close.

4. How Physicists Argue

- In math, if two numbers coincide up to 13 digits, they may still turn to be different: e.g., 1 and $1 + 10^{-100}$.
- In physics, if two quantities coincide up to a very high accuracy, it is a good indication that they are equal.
- A typical physicist argument is that:
  - while numbers like $1 + 10^{-100}$ (or $c \cdot (1 + 10^{-100})$) are, in principle, possible,
  - they are *abnormal* (not *typical*).
- In physics, second order terms like $a \cdot \Delta x^2$ of the Taylor series can be ignored if Δx is small, since:
  - while abnormally high values of a (e.g., $a = 10^{40}$) are mathematically possible,
  - typical (= not abnormal) values appearing in physical equations are usually of reasonable size.

5. How to Formalize the Physicist's Intuition of Typical (Not Abnormal): Main Idea

- To some physicist, all the values of a coefficient a above 10 are abnormal.
- To another one, who is more cautious, all the values above 10 000 are abnormal.
- For every physicist, there is a value n such that all value above n are abnormal.
- This argument can be generalized as a following property of the set $\mathcal{T}$ of all typical elements.
- Suppose that we have a monotonically decreasing sequence of sets $A_1 \supseteq A_2 \supseteq \ldots$ for which $\bigcap\limits_n A_n = \emptyset$.
- In the above example, A_n is the set of all numbers $\geq n$.
- Then, there exists an integer N for which $\mathcal{T} \cap A_N = \emptyset$.

6. How to Formalize the Physicist's Intuition of Typical (Not Abnormal): Resulting Definition

- **Definition.** *We thus say that* $\mathcal{T}$ *is a* set of typical elements *if:*
  - *for every definable decreasing sequence* $\{A_n\}$ *for which* $\bigcap\limits_n A_n = \emptyset$,
  - *there exists an* N *for which* $\mathcal{T} \cap A_N = \emptyset$.
- *Comment.* Of course, to make this definition precise,
  - we must restrict definability to a *subset* of properties,
  - so that the resulting notion of definability will be defined in ZFC itself.

7. Kolmogorov's Definition of Algorithmic Randomness

- *Kolmogorov:* proposed a new definition of a random sequence, a definition that separates
  - physically random binary sequences, e.g.:
    - sequences that appear in coin flipping experiments,
    - sequences that appear in quantum measurements
  - from sequence that follow some pattern.
- *Intuitively:* if a sequence s is random, it satisfies all the probability laws.
- *What is a probability law:* a statement S which is true with probability 1: $P(S) = 1$.
- *Conclusion:* to prove that a sequence is not random, we must show that it does not satisfy one of these laws.

8. Kolmogorov's Definition of Algorithmic Randomness (cont-d)

- *Reminder:* a sequence s is not random if it does not satisfy one of the probability laws S.
- *Equivalent statement:* s is not random if $s \in C$ for a (definable) set C $(= -S)$ with $P(C) = 0$.
- *Resulting definition* (Kolmogorov, Martin-Löf): s is random if $s \notin C$ for all definable C with $P(C) = 0$.
- *Consistency proof:*
  - Every definable set C is defined by a finite sequence of symbols (its definition).
  - Since there are countably many sequences of symbols, there are countably many definable sets C.
  - So, the complement $-\mathcal{R}$ to the class $\mathcal{R}$ of all random sequences also has probability 0.

9. Towards a More Physically Adequate Versions of Kolmogorov Randomness

- *Problem:* the 1960s Kolmogorov's definition only explains why events with probability 0 do not happen.
- *What we need:* formalize the physicists' intuition that events with very small probability cannot happen.
- *Seemingly natural formalization:* there exists the "smallest possible probability" p_0 such that:
  - if the computed probability p of some event is larger than p_0, then this event can occur, while
  - if the computed probability p is $\le p_0$, the event cannot occur.
- *Example:* a fair coin falls heads 100 times with prob. 2^{-100}; it is impossible if $p_0 \ge 2^{-100}$.

10. The Above Formalization of Randomness is Not Always Adequate

- *Problem:* every sequence of heads and tails has exactly the same probability.
- *Corollary:* if we choose $p_0 \geq 2^{-100}$, we will thus exclude all sequences of 100 heads and tails.
- However, anyone can toss a coin 100 times.
- This proves that some such sequences are physically possible.
- *Similar situation:* Kyburg's lottery paradox:
  - in a big (e.g., state-wide) lottery, the probability of winning the Grand Prize is very small;
  - a reasonable person should not expect to win;
  - however, some people do win big prizes.

11. New Definition of Randomness

- *Example:* height:
  - if height is ≥ 6 ft, it is still normal;
  - if instead of 6 ft, we consider 6 ft 1 in, 6 ft 2 in, etc., then $\exists h_0$ s.t. everyone taller than h_0 is abnormal;
  - we are not sure what is h_0, but we are sure such h_0 exists.
- *General description:* on the universal set U, we have sets $A_1 \supseteq A_2 \supseteq \ldots \supseteq A_n \supseteq \ldots$ s.t. $P(\cap A_n) = 0$.
- *Example:* A_1 = people w/height ≥ 6 ft, A_2 = people w/height ≥ 6 ft 1 in, etc.
- A set $\mathcal{R} \subseteq U$ is called a *set of random elements* if

  $\forall$ definable sequence of sets A_n for which $A_n \supseteq A_{n+1}$ for all n and $P(\cap A_n) = 0$, $\exists N$ for which $A_N \cap \mathcal{R} = \emptyset$.

12. Coin Example

- Universal set $U = \{\mathrm{H}, \mathrm{T}\}^{\mathbb{N}}$
- Here, A_n is the set of all the sequences that start with n heads.
- The sequence $\{A_n\}$ is decreasing and definable, and its intersection has probability 0.
- Therefore, for every set $\mathcal{R}$ of random elements of U, there exists an integer N for which $A_N \cap \mathcal{R} = \emptyset$.
- This means that if a sequence $s \in \mathcal{R}$ is random and starts with N heads, it must consist of heads only.
- *In physical terms:* it means that

  a random sequence cannot start with N heads.

- This is exactly what we wanted to formalize.

13. Relation between Typical and Random

- A set $\mathcal{R} \subseteq U$ is called a *set of random elements* if

  $\forall$ definable sequence of sets A_n for which $A_n \supseteq A_{n+1}$ for all n and $P(\cap A_n) = 0$, $\exists N$ for which $A_N \cap \mathcal{R} = \emptyset$.

- A set $\mathcal{T} \subseteq U$ is called a *set of typical elements* if

  $\forall$ definable sequence of sets A_n for which $A_n \supseteq A_{n+1}$ for all n and $\cap A_n = \emptyset$, $\exists N$ for which $A_N \cap \mathcal{R} = \emptyset$.

- *Relation:* let $\mathcal{R}_K$ is the set of the elements random in the usual Komogorov-Martin-Löf sense. Then:
  - every set of random elements is also a set of typical elements (since if $\cap A_n = \emptyset$ then $P(A_n) \to 0$);
  - for every set of typical elements $\mathcal{T}$, the intersection $\mathcal{T} \cap \mathcal{R}_K$ is a set of random elements.

- If $P(\cap A_n) = 0$ then for $B_m \stackrel{\text{def}}{=} A_m - \cap A_n$, $B_m \supseteq B_{m+1}$, $\cap B_n = \emptyset$, so $\exists N\ (B_N \cap \mathcal{T} = \emptyset)$; and $(\cap A_n) \cap \mathcal{R}_K = \emptyset$.

14. Ill-Posed Problems: In Brief

- Main *objectives* of science:
  - *guaranteed* estimates for physical quantities;
  - *guaranteed* predictions for these quantities.
- *Problem:* estimation and prediction are ill-posed.
- *Example:*
  - measurement devices are inertial;
  - hence suppress high frequencies ω;
  - so $\varphi(x)$ and $\varphi(x) + \sin(\omega \cdot t)$ are indistinguishable.
- *Existing approaches:*
  - statistical regularization (filtering);
  - Tikhonov regularization (e.g., $|\dot{x}| \le \Delta$);
  - expert-based regularization.
- *Main problem:* no guarantee.

15. On "Not Abnormal" Solutions, Problems Become Well-Posed

- *State estimation – an ill-posed problem:*
  - *Measurement* f*:*
    state $s \in S \to$ observation $r = f(s) \in R$.
  - *In principle,* we can reconstruct $r \to s$:
    as $s = f^{-1}(r)$.
  - *Problem:* small changes in r can lead to huge changes in s (f^{-1} *not continuous*).
- *Theorem:*
  - Let S be a definably separable metric space.
  - Let $\mathcal{T}$ be a set of all not abnormal elements of S.
  - Let $f : S \to R$ be a continuous 1-1 function.
  - Then, the inverse mapping $f^{-1} : R \to S$
    is *continuous* for every $r \in f(\mathcal{T})$.

16. Another Physically Interesting Consequence: Justification of Physical Induction

- *What is physical induction:* a property P is satisfied in the first N experiments, then it is satisfied always.
- *Comment:* N should be sufficiently large.
- *Theorem:* $\exists N$ s.t. if for a typical object o, P is satisfied in the first N experiments, then P is satisfied always.
- *Notation:* $s \stackrel{\text{def}}{=} s_1 s_2 \ldots$, where:
  - $s_i = T$ if P holds in the i-th experiment, and
  - $s_i = F$ if $\neg P$ holds in the i-th experiment.
- *Proof:* $A_n \stackrel{\text{def}}{=} \{o : s_1 = \ldots = s_n = T \,\&\, \exists m\,(s_m = F)\}$; then $A_n \supseteq A_{n+1}$ and $\cup A_n = \emptyset$ so $\exists N\,(A_N \cap \mathcal{T} = \emptyset)$.
- *Meaning* of $A_N \cap \mathcal{T} = \emptyset$: if $o \in \mathcal{T}$ and $s_1 = \ldots = s_N = T$, then $\neg\exists m\,(s_m = F)$, i.e., $\forall m\,(s_m = T)$.

17. When We Restrict Ourselves to Typical Elements, Algorithms Become Possible

- *New result:* for every set of typical pairs of real numbers $\mathcal{T} \subseteq \mathbb{R}^2$, there exists an algorithm, that,
  - given real numbers $(x, y) \in \mathcal{T}$,
  - decides whether $x = y$ or not.
- *Idea:* for $A_n = \{(x, y) : 0 < d(x, y) < 2^{-n}\}$, we have $A_n \supseteq A_{n+1}$ and $\cap A_n = \emptyset$, so $\exists N \, (A_N \cap \mathcal{T} = \emptyset)$.
- *Meaning:* if $(x, y) \in \mathcal{T}$, then $d(x, y) = 0$ (i.e., $x = y$) or $d(x, y) \geq 2^{-N}$.
- *Algorithm:* compute $d(x, y)$ with accuracy $2^{-(N+2)}$, i.e., compute d such that $|d(x, y) - d| \leq 2^{-(N+2)}$:
  - if $d \geq 2^{-(N+1)}$, then $d(x, y) \geq d - 2^{-(N+2)} \geq 2^{-(N+1)} - 2^{-(N+2)} > 0$, hence $x \neq y$;
  - if $d < 2^{-(N+1)}$, then $d(x, y) \leq d + 2^{-(N+2)} \leq 2^{-(N+1)} + 2^{-(N+2)} < -2^{-N}$, hence $x = y$.

18. When We Restrict Ourselves to Typical Elements, Algorithms Become Possible (cont-d)

- There exists an algorithm that:
  - given a typical function $f(x)$ on a computable compact K,
  - computes a value x at which $f(x) = \max\limits_y f(y)$.
- There exists an algorithm that:
  - given a typical function $f(x)$ on a computable compact K that attains a 0 value somewhere on K,
  - computes a value x at which $f(x) = 0$.
- Moreover, we can compute 2^{-n}-approximations to the corresponding sets:

$$\{x : f(x) = \max_y f(y)\} \text{ and } \{x : f(x) = 0\}.$$

19. Proof: Main Idea

- To compute $R \stackrel{\text{def}}{=} \{x : f(x) = 0\}$ with accuracy $\varepsilon > 0$, take an $(\varepsilon/2)$-net $\{x_1, \ldots, x_n\} \subseteq K$.
- For each i, we can compute $\varepsilon' \in (\varepsilon/2, \varepsilon)$ for which $B_i \stackrel{\text{def}}{=} \{x : d(x, x_i) \le \varepsilon'\}$ is a computable compact set.
- Thus, we can compute $m_i \stackrel{\text{def}}{=} \min\{|f(x)| : x \in B_i\}$.
- As before, $\exists N\, \forall f \in \mathcal{T}\, \forall i\, (m_i = 0 \vee m_i \ge 2^{-N})$.
- Thus, by computing each m_i with accuracy $2^{-(N+2)}$, we can check whether $m_i = 0$ or $m_i > 0$.
- We claim that $d_H(R, \{x_i : m_i = 0\}) \le \varepsilon$.
- $m_i = 0 \Rightarrow \exists x\, (f(x) = 0\, \&\, d(x, x_i) < \varepsilon) \Rightarrow d(x_i, R) \le \varepsilon$.
- If $x \in R$, i.e., $f(x) = 0$, then $\exists i\, (d(x, x_i) \le \varepsilon/2)$ hence $m_i = 0$ and $x_i \in \{x_i : m_i = 0\}$.
- $f(x) = \max\limits_y f(y) \Leftrightarrow g(x) \stackrel{\text{def}}{=} f(x) - \max\limits_y f(y) = 0$.

20. Other Problems

- Is it possible to similarly compute the optimal *minimax* strategies, i.e., find x such that

$$\min_y f(x,y) = \max_z \min_y f(z,y)?$$

- Yes, this is the same as finding location of the maximum of a computable function $g(x) \stackrel{\text{def}}{=} \min_y f(x,y)$.
- It is possible to similarly compute *Pareto optimum* set:
  - we have several objective functions $f_1(x), \ldots, f_n(x)$;
  - we say that y is *better* than x if

$$\forall i\,(f_i(y) \geq f_i(x))\,\&\,\exists i\,(f_i(y) > f_i(x));$$

  - an alternative x is *Pareto-optimal* if no other alternative y is better than x.
- Is it possible to similarly compute the set of *local maxima (minima)*?

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22. Definable: Mathematical Comment

- *What is definable:*
  - let $\mathcal{L}$ be a theory,
  - let $P(x)$ be a formula from the language of the theory $\mathcal{L}$, with one free variable x
  - so that the set $\{x \mid P(x)\}$ is defined in $\mathcal{L}$.

  We will then call the set $\{x \mid P(x)\}$ $\mathcal{L}$*-definable.*
- *How to deal with definable sets:*
  - Our objective is to be able to make mathematical statements about $\mathcal{L}$-definable sets.
  - Thus, we must have a stronger theory $\mathcal{M}$ in which the class of all $\mathcal{L}$-definable sets is a countable set.
  - One can prove that such $\mathcal{M}$ always exists.

23. Consistency Proof

- *Statement:* $\forall \varepsilon > 0$, there exists a set $\mathcal{T}$ of typical elements for which $\underline{P}(\mathcal{T}) \geq 1 - \varepsilon$.
- There are countably many definable sequences $\{A_n\}$: $\{A_n^{(1)}\}$, $\{A_n^{(2)}\}$, ...
- For each k, $P\left(A_n^{(k)}\right) \to 0$ as $n \to \infty$.
- Hence, there exists N_k for which $P\left(A_{N_k}^{(k)}\right) \leq \varepsilon \cdot 2^{-k}$.
- We take $\mathcal{T} \stackrel{\text{def}}{=} - \bigcup\limits_{k=1}^{\infty} A_{N_k}^{(k)}$. Since $P\left(A_{N_k}^{(k)}\right) \leq \varepsilon \cdot 2^{-k}$, we have

$$\overline{P}\left(\bigcup_{k=1}^{\infty} A_{N_k}^{(k)}\right) \leq \sum_{k=1}^{\infty} P\left(A_{N_k}^{(k)}\right) \leq \sum_{k=1}^{\infty} \varepsilon \cdot 2^{-k} = \varepsilon.$$

- Hence, $\underline{P}(\mathcal{T}) = 1 - \overline{P}\left(\bigcup\limits_{k=1}^{\infty} A_{N_k}^{(k)}\right) \geq 1 - \varepsilon$.

24. Proof of Well-Posedness

- *Known:* if a f is continuous and 1-1 on a compact, then f^{-1} is also continuous.
- *Reminder:* X is compact if and only if it is closed and for every ε, it has a finite ε-net.
- *Given:* S is definably separable.
- *Means:* $\exists$ def. $s_1, \ldots, s_n, \ldots$ everywhere dense in S.
- *Solution:* take $A_n \stackrel{\text{def}}{=} -\bigcup\limits_{i=1}^{n} B_\varepsilon(s_i)$.
- Since s_i are everywhere dense, we have $\cap A_n = \emptyset$.
- Hence, there exists N for which $A_N \cap \mathcal{T} = \emptyset$.
- Since $A_N = -\bigcup\limits_{i=1}^{N} B_\varepsilon(s_i)$, this means $\mathcal{T} \subseteq \bigcup\limits_{i=1}^{N} B_\varepsilon(s_i)$.
- Hence $\{s_1, \ldots, s_N\}$ is an ε-net for $\mathcal{T}$. Q.E.D.

25. Other Practical Use of Algorithmic Randomness: When to Stop an Iterative Algorithm

- *Situation* in numerical mathematics:
  - we often know an iterative process whose results x_k are known to converge to the desired solution x,
  - but we do not know when to stop to guarantee that

$$d_X(x_k, x) \leq \varepsilon.$$

- *Heuristic approach:* stop when $d_X(x_k, x_{k+1}) \leq \delta$ for some $\delta > 0$.
- *Example:* in physics, if 2nd order terms are small, we use the linear expression as an approximation.

26. When to Stop an Iterative Algorithm: Result

- Let $\{x_k\} \in S$, k be an integer, and $\varepsilon > 0$ a real number.
- We say that x_k is *ε-accurate* if $d_X(x_k, \lim x_p) \le \varepsilon$.
- Let $d \ge 1$ be an integer.
- By a *stopping criterion*, we mean a function $c : X^d \to R_0^+$ that satisfies the following two properties:
  - If $\{x_k\} \in S$, then $c(x_k, \ldots, x_{k+d-1}) \to 0$.
  - If for some $\{x_n\} \in S$ and k, $c(x_k, \ldots, x_{k+d-1}) = 0$, then $x_k = \ldots = x_{k+d-1} = \lim x_p$.
- *Result:* Let c be a stopping criterion. Then, for every $\varepsilon > 0$, there exists a $\delta > 0$ such that
  – if $c(x_k, \ldots, x_{k+d-1}) \le \delta$, and the sequence $\{x_n\}$ is not abnormal,
  – then x_k is ε-accurate.

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