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Hilbert's Sixth Problem:

Descriptive Statistics as New Foundations for Probability

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RESUMEN

Hay esbozos según los cuales las probabilidades se cuentan como la fundación de la teoría matemática de las estadísticas. Mas la significación física de las probabilidades matemáticas son oscuros, muy poco entendidos. Pareciera mejor que las probabilidades físicas se fundaran en las estadísticas descriptivas de datos físicos. Se trata una teoría que así responde a una cuestión de Hilbert propuesta en su Problema Número Seis, la axiomatización de la Física. Esta está basada en la auto-correlación de las series temporales. Casi todas de las funciones de auto-correlación de las trayectorias de un sistema dinámico lineal (con un número bastante grande de grados de libertad) son todas aproximadamente iguales, no importan las condiciones iniciales, aún si el sistema no sea ergódico, como conjeturó Khintchine en 1943.

Usually, the theory of probability has been made the foundation for the theory of statistics. But the physical significance of the concept of probability is problematic, with no consensus. It would seem better to make the descriptive statistics of physical data the foundations of physical probability. This will answer a question posed by Hilbert in his Sixth Problem, the axiomatization of Physics. It is based on the auto-correlation function of time series. Almost all trajectories of a linear dynamical system (with sufficiently many degrees of freedom) are approximately equal, no matter their initial conditions, even when the system is not ergodic, as conjectured by Khintchine in 1943.

Introduction

Hilbert's Sixth Problem [1] was the Axiomatization of Physics. He had in mind not only the axiomatization of true physical theories, but as well the axiomatization of theories which would bear an interesting resemblance to, along with instructive differences from, the real world. Because of the contemporary controversies about the logical relations between Analytical Mechanics and Thermodynamics precipitated by the work of Maxwell and Boltzmann, which involved both Poincaré and Zermelo, Hilbert explicitly pointed

the need for logical foundations for the theory of probability. With Quantum Mechanics and Born's rule's having placed probability at an even more central location in the foundations of physical theory, Hilbert's prescience is remarkable. Readers younger than Hilbert may not realize that for Hilbert and his generation, Probability was not a branch of Mathematics, it was a branch of Physics.* Hilbert realized that as a preliminary to this, one would have to bring the theory of probability into mathematics proper by axiomatizing it in such a way as to clarify its relationships to Arithmetic or Geometry. Fréchet, Weyl, and Kolmogoroff did precisely this, but Kolmogoroff well knew that this did not solve the problem of clarifying the logical foundations of what is nowadays called "physical probability." He returned to this more difficult and more important part of Hilbert's Problem several times in his later career [3].

In Dirac's formulation of the axioms of Quantum Mechanics, we find the typical physicist's approach to this problem.

"If the experiment is repeated a large number of times it will be found that for each particular result will be obtained a definite fraction of the total number of times, so that one can say there is a definite probability of its being obtained any time the experiment is performed." [4]

This is not a definition at all. Such notions have been insightfully criticized in the past by Burnside [5], Littlewood [6], and Kolmogoroff [7], all three accomplished probabilists.

* This point is illustrated by Corry: he found in the Göttingen archives the list of topics for a course Hilbert taught: "In 1905 he taught a course on the axiomatic method in physics. He presented for the first time a panoramic view of various physical disciplines from an axiomatic perspective: mechanics, thermodynamics, probability calculus, kinetic theory, insurance mathematics, electrodynamics, psychophysics." [2]

In an address to a math club, Littlewood explained at length “The Dilemma of Probability Theory.”

“Now [it] cannot assert a certainty about a particular number n of throws such as ‘the proportion of 6’s will certainly be within $p \pm \epsilon$ for large enough n . . . It can only say ‘the proportion will lie within $p \pm \epsilon$ with at least such and such probability (depending on ϵ and n_o) . . .

“The vicious circle is apparent.”

“It is natural to believe that if (with the natural reservations) an act like throwing a die is repeated n times the proportion of 6’s will, with certainty, tend to a limit, p say, as $n \rightarrow \infty$. (Attempts are made to sublimate the limit into some Pickwickian sense—‘limit’ in inverted commas. But either you mean the ordinary limit, or else you have the problem of explaining how ‘limit’ behaves and you are no further. You do not make an illegitimate conception legitimate by putting it into inverted commas.) . . .

“It is generally agreed that the frequency theory won’t work. But whatever the theory it is clear that the vicious circle is very deep-seated: certainty being impossible, whatever [it] is made to state can be stated only in terms of ‘probability’. One is tempted to the extreme rashness of saying that the problem is insoluble (within our current conceptions). More sophisticated attempts than the frequency theory have been made, but they fail in the same sort of way.”

Kolmogoroff, in a chapter [7] meant for a broad scientific audience, analyzed logical circularity in the same way, and ten years later, having despaired of the possibility of fixing the frequency theory, began developing his theory of algorithmic complexity as the logical foundation for probability.

However, we can answer Littlewood’s objection by, indeed, carefully defining a new kind of limit, which we will call the thermodynamic limit, which evades the logical circularity of the naive frequency theory but still has physical meaning and close contact with the physical world. It has the physical content which physicists like about the frequency theory, in spite of its logical shortcomings.

The well known logician and computer scientist Prof. Jan von Plato, of Helsinki,

University, succeeded in giving a definition of probability for ergodic systems [8]. This definition is rather different from the one which will be given here, cannot be made to work for quantum systems [9], and because it does not use Khintchine's conjectures, the thermodynamic limit, is restricted to ergodic classical systems.

A sequence of dynamical systems

Suppose given a sequence M_n of dynamical systems, each one with n degrees of freedom, and equipped with a flow $x \mapsto x_t$ and an invariant measure under the flow. Suppose given an observable (i.e., a measurable function) f_n on each M_n . To simplify notation, if $v_n \in M_n$ is a perhaps implicitly fixed initial condition, we write $f_n(t) = f_n((v_n)_t)$, the change in f due to the flow. The motivation is that we are interested in $\{M_n\}$ when in some sense they are all 'the same' kind of physical system, only the number of degrees of freedom increases without bound, and f_n is 'the same' physical quantity, e.g., momentum. We will, inspired by a conjecture of Khintchine's, define the limit μ_n which, when it exists, is independent of the substitution of the μ_n by any other absolutely continuous with respect to μ_n .

For f a measurable function of time, Wiener studied the auto-correlation function

$$\varphi_f(\tau) = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T f(t + \tau) f(t) dt.$$

When one views f as an observable on M_n , it is a set of data, a time series, and the auto-correlation function is a descriptive statistic of this set of data.

Wiener further defined the higher correlation functions for any positive integer

$$\varphi_f^m(\tau_1, \tau_2, \dots, \tau_m) = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T \Pi_1^m f(t + \tau_i) dt.$$

There is no dependence on the notion of probability. In the literature, there is a conflicting definition of the auto-correlation function $R(\tau)$ of a time series, which applies to a time series which is not data, but really a stochastic process. That is, suppose given a probability space P with probability measure μ , and for each $\alpha \in P$, suppose that $f_\alpha(t)$ is a time series in the usual sense. Then the phase auto-correlation function defined by Khintchine several years after Wiener's work to be $R(t, \tau) = \int_P f_\alpha(t) f_\alpha(t + \tau) d\mu(\alpha)$ and is independent of t if the process is stationary (the notion of stationary seems to have been introduced by Khintchine at the same time). The whole point here is to avoid the problem of $R(\tau)$ it, since that might seem to re-introduce the logical circle Littlewood complained about.

The whole point of thermodynamics is to convert a sequence of deterministic dynamical systems into a stochastic process by passing to whatever kind of thermodynamic limit one has defined. Ours will be a new kind, not the same as the usual one. Balian has proposed a method for the creation of new kinds of thermodynamic limits, each one tailored for the application at hand.

Definition. In the setting above, the sequence $\{(M_n, \mu_n), f_n\}$ is said to have a thermodynamic limit if for every choice of a compact subset K of the time-axis, a positive ϵ , and a positive integer M , there exists an integer N so large that for every $n \geq N$, there is a subset N_n of M_n with $\mu_n(M_n \setminus N_n) < \epsilon$ such that for any two initial conditions $w \in N_n$,

$$|\varphi_v^m(t_1, t_2, \dots, t_m) - \varphi_w^m(t_1, t_2, \dots, t_m)| < \epsilon$$

for all $t_i \in K$ and all $m < M$. Here, φ_v^m is the m -point auto-correlation function of $f_n(v_t)$, and similarly for φ_w^m . The trajectories (or, equivalently, their initial conditions)

belonging to N_n are called *normal* and N_n is called a *normal cell*.

It is obvious that there then exists a function φ_∞ defined for all time such that $\lim_{n \rightarrow \infty} \varphi_n$ converges to φ_∞ with uniform convergence on compact sets, provided μ_n is chosen to have an initial condition from N_n . Similarly for φ_∞^m . The invariance of μ_n under T replacing μ_n by any ν_n absolutely continuous with respect to μ_n is also obvious.

Lévy's philosophy was that in order to study a stochastic process, it suffices to know its auto-correlation function $R(\tau)$, its auto-correlation function (in the sense of Khintchine) [10]. A Gaussian stationary centered stochastic process is determined up to equivalence by R . Wiener has also remarked [11] that even a non-Gaussian one is still determined up to some sort of equivalence by knowledge of all its higher m -point auto-correlation functions R^m .

Since we have a set of suitable m -point correlation functions, we would be able to define a limit object of a sequence that has a thermodynamic limit: the stochastic process whose auto-correlation functions in the sense of Khintchine are equal to the limits of the descriptive statistics of the elements of our sequence. But we do not need to define such a sort of limit object such as this for our immediate purposes. For now, we will regard f_n and f_∞ as *the limit*. One would also like to define a suitable equivalence relation on the space of sequences which possess limits and study the space of equivalence classes. In some other Hilbert problems, the solution to the Sixth opens up many avenues for further research.

The definition of event and of probability

The mathematical axiomization of probability theory has taught us that it is just as important to precisely specify what is an *event* as it is to associate a number to an

This, indeed, is a foundational point difficult for engineers or physicists to appreciate. They tend to feel that every subset is measurable. In fact, the definition of Lebesgue measure formalizes an intuition about what a ‘physically constructible’ subset of Euclidean space should be, so in a sense, non-measurable sets cannot have any physical significance.

In Quantum Mechanics, there has been the intuition that probabilities arise from the necessity of amplifying a microscopic event up to the macroscopic level (e.g., Feynman in [12]). In Classical Mechanics, there has been the intuition that probability arises from the thermodynamic limit of deterministic systems. (There have also been rival intuitions, but we will not touch on them here.) It follows from this that we should formally define an ‘event’ to be something that only arises in this way, when two contrasting scales are being compared. In particular, neither points nor subsets of a fixed M_n are events. (For this reason, neither Lebesgue measure nor Liouville measure nor μ_n are interesting as probability measures.) Taking our cue from Quantum Mechanics, only the result of a measurement is defined to be an event.

The quantum case was already treated, in the special case of the two slit experiment, in [13] and [14]. There, ‘event’ was defined as the thermodynamic limit of the result of an interaction with an amplifying apparatus: in that limit, Planck’s constant goes to zero and the amplifying apparatus becomes a classical system.

In the classical case, in Statistical Mechanics, as remarked by Wiener [15], Gudder [16], and Pauli [17], a measurement of an observable f on M is really a long-time average, modelled or approximated by the infinite time average

$$\langle f \rangle_t = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T f(t) dt,$$

where the dependence on the initial condition $v_o \in M_n$ has been suppressed. The same applies to any function of f , for example, the variance f^2 .* However, this dependence on the initial condition prevents us from turning this idea into an exact definition of equilibrium and this is the reason we pass to the thermodynamic limit. As the number of degrees of freedom grows without bound, almost all initial conditions give approximately the same answer, the expectation of f , and $\varphi_\infty(0)$ for the variance. We also obtain all the moments of the limit of f , and so a random variable f_∞ can be rigorously defined (as above) and its probability space M_∞ is taken to be the unit interval $[0,1]$ with Lebesgue measure. Physically, f_∞ is an idealisation with properties which are good approximations to the majority of the $\langle f_n \rangle_t$, $\langle f_n^2 \rangle_t$, etc., each of which is a descriptive statistic of some collection of data.

Suppose given a sequence $\{(M_n, \mu_n), f_n\}$ which has a thermodynamic limit, with associated φ_∞ , f_∞ , etc., as above.

Definition. Let the probability space P be the direct image under f_∞ of the probability space (M_∞, dx) . Then the *events* of the thermodynamic limit of $\{(M_n, \mu_n), f_n\}$ are the measurable subsets of P and the *probability* of an event F is its measure.

The definition of limit we have introduced is modelled closely on the equilibrium statistical mechanics and work of Ford, Kac, and Mazur [18]. For this reason, the measurement of a function of f yields one value with probability unity, because the system is in equilibrium.

In fact, this limit was tailor-made for measurements of f , but it will apply as well to

* In the author's view, and in the views just cited, time averages model measurements and phase averages model probabilities. Prof. von Plato, following Einstein's agreement with Landau, defines probabilities as infinite time averages.

any function of f . If f models the coin-toss (or cast of a die) dilemma of Littlewood, then f will be assumed to take only the values $\pm\frac{1}{2}$, and be centered. Composing f with the indicator function of a small neighbourhood of $\frac{1}{2}$, we get g (or, just put $g = f$). Then $\langle g \rangle_t =$ the frequency of heads.† This frequency might be zero, if the initial condition is perverse. Putting $g_\infty = f_\infty + \frac{1}{2}$, all the moments of g_∞ follow from those of f_∞ . In particular, the expectation of g_∞ , which is our definition of the probability that f takes the value “heads,” depends only on the equivalence class of the sequence $\{(M_n, \mu_n)\}$.

The physical meaning is that if the sequence was defined shrewdly, then it is a good approximation to $\langle g_{6.2.10^{23}} \rangle_t$ (a physically meaningful function) unless the initial condition does not belong to N_n , which is a determinate statement with concrete physical meaning. Of course the limit of the sequence does not change, and hence $\langle g_\infty \rangle_\mu$ does not change. If any finite number of M_n are replaced by ridiculous counterfeits, and this includes M_6 , the statement will be useless for any practical purpose, but still physically meaningful. The same applies if the initial condition is, in fact, outside of $N_{6.2.10^{23}}$. A statement will be meaningful but useless for this particular case. Many have already suspected that the true meaning of probability is an approximate one with a certain range of validity, and when used outside the limits of that range, will lead to paradox.

* If one were to construct the obvious stochastic process from the idea of repeated coin-tossing, the process would not be stationary in continuous time. But in our descriptive statistics, there is no assumption of stationarity.

† For us, frequency is not equal to probability. What is measured is frequency. Frequency is related in a subtle way to the probability, just as time averages are related to phase averages.

practically useless statements. And the point of the Hilbert problem is only to tidy up the logical structure of probability statements, not to impose a tidiness on the world that does not exist.

Ever since the work of Wiener, physicists and engineers have had the intuition that a time series whose auto-correlation function has an absolutely continuous power spectrum is “random.” This can be made precise in the context of our definition. If the coin-toss results from $\{(M_n, \mu_n), f_n\}$, as above, then we can use the auto-correlation of a sequence of unit pulses as a measure of how random the sequence is. If its auto-correlation function is *normal*, i.e., approximately equal to that of all the others from N_n , then the sequence is approximately random. Thus, the auto-correlation function can be used instead of algorithmic complexity.

The assertion that the probabilities in the thermodynamic limit are good approximations to the real situation of $M_{6.2 \cdot 10^{23}}$ is testable, by experiment. In principle, one should be able to calculate how large n has to be for the predictions based on calculations using the limit are falsified by an experimental run $v_o \notin N_n$. That said, the practical purpose of using thermodynamic limits is precisely to avoid having to make calculations about M_n , which are practically impossible, substituting them for calculations about M_∞ , which are easier.

A class of examples

We will show that this definition is not vacuous by studying an interesting class of examples: Hamiltonian systems of linearly coupled harmonic oscillators. These systems are completely integrable, but in the limit, they exhibit the kind of very very weak ergodicity

conjectured by Khintchine in 1943 [19] for a (hopefully) much larger class of dynamical systems (he did not concretely specify which class). The first point is that the system is simple enough that the calculations for M_n can be carried out. The second point is that ergodicity is usually associated with non-linearity, but here are linear systems where the macro-level are practically indistinguishable from ergodic systems.

The third point is that from the standpoint of the foundations of Physics, only Quantum Mechanics is truly important, not Classical Mechanics, and quantum systems are linear Hamiltonian systems. So we will study the general class of linearly coupled harmonic oscillators as in [20].

Obviously not every sequence of systems M_n , even if possessing a limit, will exhibit weakly ergodic behaviour even if n , the dimension of the space, increases without bound. The intuition from equilibrium statistical mechanics is that each M_n must be composed of many identical parts (or, more generally, a fixed number of different types of parts with the number of parts of the same type increasing without bound), and there must be a coupling between the parts. Furthermore, a natural hypothesis to make is that the interaction between part i and part j only depends on the relative situation of i and j (that if k and l constitute a parallel pair, their interaction term should be the same), which leads naturally to the study of an interaction matrix A_n which is cyclic (and, of course, symmetric).

We will generalize the result of [20], which in turn was a generalization of the result of Ford, Kac, and Mazur [18]. The main point here is only to show how the new definition of probability and event applies in this situation. The main interest is that the same

of definition of *probability* and *event* works for classical physics as was used earlier, and [14], for the quantum mechanical measurement of a two-state system by an apparatus in a state of negative temperature. The second point of interest is that we will have introduced the notion of probability without relying on imposing a particular probability distribution on M_n . This opens the way, in the future, to studying systems in a negative temperature state, where the usual notion of probability distribution cannot be used.

Notation. If n is even, choose M_n to be the same as M_{n-1} . From now on, assume n odd, and equal to $2N + 1$. All indices will run from $-N$ to N , except angles, which will run from epsilon above $-\pi$ to epsilon below π : we put $\theta_l = \frac{2\pi l}{n}$ for $l = -N, \dots, N$.

M_n is a Hamiltonian dynamical system (or, rather, the restriction of one to a surface of constant energy, see later) with canonical co-ordinates p_i, q_i and Hamiltonian H_n

$$H_n = \sum_{i=-N}^N \frac{p_i^2}{2m} + \frac{1}{2} (q_{-N}, q_{-N+1}, \dots, q_N) A \begin{pmatrix} q_{-N} \\ q_{-N+1} \\ \vdots \\ q_N \end{pmatrix}$$

where A is a symmetric $n \times n$ square real matrix with positive eigenvalues ω_l^2 satisfying

$$(A)_{ml} = \frac{1}{n+1} \sum_{k=-N}^N \omega_k^2 e^{\frac{2\pi\sqrt{-1}}{n+1} k(m-l)}.$$

This is obviously symmetric if we make a simple assumption on the ω_l 's.

We have

$$p_o(t) = \frac{1}{n} \left\{ \sum_k \sum_l \cos(\omega_l t) \zeta^{-lk} p_k(0) - \sum_k \sum_l \omega_l \sin(\omega_l t) \zeta^{-lk} q_k(0) \right\}.$$

Putting $\hat{p}(k) = \sum_i \zeta^{-ik} p_i(0)$ and similarly for \hat{q} , this becomes

$$(1) \quad p_o(t) = \frac{1}{n} \left\{ \sum_k \hat{p}(k) \cos(\omega_k t) - \sum_k \hat{q}(k) \omega_k \sin(\omega_k t) \right\}.$$

Furthermore, the auto-correlation function of p_o is

$$(2) \quad \varphi(\tau) = \sum_k \frac{1}{2} \left(\frac{1}{2N+1} \right)^2 (|\widehat{p}(k)|^2 + |\omega_k \widehat{q}(k)|^2) \cos(\omega_k t),$$

and the higher auto-correlation functions vanish for an odd number of points and are non-zero for an even number of points, are trigonometric polynomials with more or less the same coefficients.

We will take p_o as our observable f_n , and the restriction of Liouville measure to any surface of constant energy E as our invariant measure μ_n . The dynamical system M_n will be the surface of constant energy. The energy level E_n is defined for traditional reasons, and to make the comparison with traditional results convenient, to be that energy level which is most probable according to the Maxwell distribution: it is $\frac{n}{kT}$, where k is Boltzmann's constant and T is the absolute temperature in degrees Kelvin.

To implement the notion that the M_n are the same but different, we will suppose that their eigenvalues are taken from the same function ω but evaluated at different points. Suppose that we know the eigenvalues ω_l for the real system $M_{6.2.10^{23}}$ which we are interested in. Regarding ω_l as a function of θ_l , write it as $\omega(\theta_l) = \omega_l$. But now regard ω as a continuous function on $(-\pi, \pi)$ by interpolating the given values in some sensible fashion. (One can make this makes intuitive physical sense.)

For any n , define the Hamiltonian of M_n by putting $\omega_s = \omega(\frac{2\pi s}{n})$. Then the surface measure Equation 1 become Riemann sums for the improper integrals

$$\frac{1}{2\pi} \int_{-\pi}^{\pi} \widehat{p}(\theta) \cos(\omega(\theta)t) d\theta - \int_{-\pi}^{\pi} \widehat{q}(\theta) \omega(\theta) \sin(\omega(\theta)t) d\theta.$$

Now the same methods of proof of the theorem of [20] show that

Theorem. Suppose that ω is a continuous function on $(-\pi, \pi)$ such that the Riemann integrals

$$\int_{-\pi+\delta}^{\pi-\delta} \omega(\theta) \cos(m\theta) d\theta$$

converge for every m and every small positive δ . Using ω , define $\{(M_n, \mu_n), f_n\}$ as in (1). Then this sequence has a thermodynamic limit, and

$$\varphi_\infty(\tau) = \frac{1}{2\pi} \int_{-\pi}^{\pi} \cos(\omega(\theta)\tau) d\theta.$$

Corollary. In fact, since the coefficients are more or less the same for all the f_n , the multi-point auto-correlation functions as they are for the ordinary one φ , the proof goes through more. It shows the uniformity in M of our estimates, and hence, this sequence satisfies a stronger condition than is necessary for the definition of limit: the conclusion holds for all m simultaneously.

We omit the details of the proof of the corollary.

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