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BULLETIN N° 225
ACADÉMIE EUROPEENNE INTERDISCIPLINAIRE DES SCIENCES
INTERDISCIPLINARY EUROPEAN ACADEMY OF SCIENCES

Mardi 15 mai 2018 17h Maison de l'AX:

1. **15h45 Conférence par Alexeï GRINBAUM**
   Larsim/CEA Saclay
   "Corrélations quantiques et postquantiques"
2. **17h Présentation par nos collègues de l'AEIS Nancy**
   Jean-Louis REYNET et Bruno DEFFAINS
   de leurs projets de futur Colloque
3. **Vote sur une demande d'admission à l'AEIS en tant que membre correspondant**

Notre Prochaine séance aura lieu le lundi 11 juin 2018 à 16h
à l'Institut Henri Poincaré salle 204
11, rue Pierre et Marie Curie 75005 PARIS/Métro : RER Luxembourg

Elle aura pour thème

1. **Vote sur une demande d'admission à l'AEIS en tant que membre titulaire**
2. **Vote sur le choix de la thématique du prochain colloque AEIS 2020 (ou 2021)**

Académie Européenne Interdisciplinaire des Sciences
Siège Social : 5 rue Descartes 75005 Paris
http://www.science-inter.com

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Mai 2018

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Prochaine séance : lundi 11 juin 2018

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5 rue Descartes 75005 PARIS

Séance du Mardi 15 mai 2018/Maison de l'AX

La séance est ouverte à 15h45, **sous la Présidence de Victor MASTRANGELO** et en la présence de nos Collègues Gilbert BELAUBRE, Gilles COHEN-TANNOUDJI, Sylvie DERENNE, Claude ELBAZ, Michel GONDRAN, Irène HERPE-LITWIN, Antoine LONG, Claude MAURY, Jacques PRINTZ, Jean SCHMETS, Alain STAHL.

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Etait présent en tant que membre correspondant notre Collègue Dominique PRAPOTCHNIK
Etait présent en tant qu'invité Jean BERBINAU administrateur du Lycée Saint Louis et Collège Stanislas

I. Conférence "Corrélations quantiques et postquantiques" par Alexeï GRINBAUM Larsim/CEA Saclay

A. Présentation du conférencier Alexeï GRINBAUM

Né le 30 novembre 1978 à St Petersburg Russie, Alexeï GRINBAUM , de nationalité franco-russe, exerce les fonctions suivantes:

- depuis 2006, chercheur au LARSIM (Laboratoire de Recherche sur les Sciences de la Matière) au CEA à Saclay.
- Il est également depuis 2007 enseignant à l'ENSTA, à l'Université d'Evry, à l'Ecole du Val-de-Grâce.
- Il est également enseignant occasionnel à l'Ecole Normale Supérieure, l'Ecole Polytechnique, l'nstitut Pasteur, l'INSTN, l'Ecole Centrale, Sciences Po, et à l'Université Européenne de St Petersburg et à l'Institut Gustave Roussy. après avoir exercé différents postes de post-doctorants en France et au Canada.

Il est également visiteur chercheur à l' Institut d'Optique quantique et d'Information quantique de Vienne (Autriche) , à l'Université de Yale(USA); au Perimeter Institute for Theoretical Physics (Canada), et à l'Université de Pavie (Italie).

Sa formation peut se résumer comme suit:

2004	Ph.D. en philosophie des sciences CREA, Ecole Polytechnique)
2003	Master.Sciences. en physique théorique (Université d'Etat de St. Petersburg).
2001	DEA de Sciences cognitives (Ecole Polytechnique)

Il parle couramment russe, anglais, français et italien.

Par ailleurs, il est membre entre autres des sociétés suivantes:

- Membre de la Commission de réflexion sur l'Ethique de la Recherche en sciences et technologies du Numérique d'ALLISTENE (CERNA), depuis 2012
- Membre du Groupe de travail sur les impacts économiques et sociaux de l'intelligence artificielle du Gouvernement français (2017)
- Membre du General Principles Committee of the IEEE Global Initiative for Ethical Considerations in Artificial Intelligence and Autonomous Systems (depuis 2016)
- Expert de la Commission Européenne pour l'évaluation éthique des projets de recherche (depuis 2016)
- Membre du Groupe de Travail Ethique, Juridique, Normalisation & Réglementaire de France Robot Initiative, 2014-2015
- Membre du Advisory Board of STS research project "Russian Computer Scientists at home and abroad" (European University in St Petersburg), 2014
- Membre du Groupe de travail « L'impact de la technologie sur la vie des hommes », Centre d'analyse stratégique, Secrétariat d'Etat chargé de la Prospective, 2008
- The Estate of Joseph Brodsky, representative (depuis1997)
- Joseph Brodsky Memorial Fellowship Fund, special consultant (since 2004)

Il est membre du comité de réflexion de nombreuses publications internationales, telles que :

Nature, British Journal for the Philosophy of Science, Studies in the History and Philosophy of Modern Physics, Foundations of Physics, Foundations of Science, Proceedings of Royal Society *A*, Annales Henri Poincaré, Philosophia Scientiæ, Comptes Rendus de l'Académie des Sciences – Geosciences, NanoEthics, Science and Engineering Ethics, Mind and Matter, Minds and Machines, Revue d'histoire des sciences, Axioms, PLOS, Journal of Responsible Innovation, Entropy, European Journal for Philosophy of Science, Life Sciences, Society and Policy

Il a participé à 195 colloques internationaux....

B. Présentation par Alexeï GRINBAUM de " Corrélations quantiques et post quantiques"

Le résumé de la présentation (déjà communiqué) est le suivant:

La quantité de corrélations permises par l'intrication quantique est supérieure à la borne classique mais inférieure à ce qui est mathématiquement possible. Pourquoi cette limite arbitraire? Est-ce une constante de la Nature, une complexité liée à un artefact de l'esprit humain? Je passerai en revue plusieurs tentatives récentes pour lui donner un sens en étudiant des modèles "postquantiques".

Un compte-rendu détaillé sera prochainement disponible sur le site de l'AEIS , http://www.science-inter.com

II. Présentation des thématiques possibles pour un futur colloque

Les diverses thématiques ont été exposées et transmises aux membres titulaires de l'AEIS qui voteront sur le choix de la thématique à retenir, le lundi 11 juin.

Annonces

I. Notre Collègue Alain STAHL vient de publier auprès de la Librairie Philosophique VRIN la 3ème édition de son ouvrage "*Science et Philosophie*"

Cet ouvrage de 337 pages est consacré à une réflexion sue les conséquences épistémologiques et philosophiques des avancées spectaculaires dans tous les domaines scientifiques. Il renvoie à d'importants développements donnés en libre accès sur le site de l'auteur http://perso.wanadood.fr/alain.stahl

Les apports nouveaux, dans cette troisième édition, concernent :

1 - des acquis récents qui étayent ses réflexions de « critique scientifique » sur des points d'actualité, tels que le calcul informatique, les transitions de phase, la cosmologie, le repliement des protéines, l'intelligence artificielle, les méthodes de mesure...
2 - Un dernier chapitre, entièrement nouveau, où – par une méthode originale, récapitulant les conclusions des chapitres scientifiques – l'auteur tente de répondre à la question posée par le nouveau sous-titre de l'ouvrage. : “La science permet-elle une présentation moderne des grandes questions philosophiques?”
L'écriture est rigoureuse, mais la lecture est aisée.

Les grands thèmes philosophiques sont toujours, –chose rare -, étayés par la priorité donnée aux acquis scientifiques. C'est une mise à niveau dont la lecture induit un dialogue permanent, très ouvert et très riche, avec l'auteur.

II. Quelques ouvrages papiers relatifs au colloque de 2014 " Systèmes stellaires et planétaires- Conditions d'apparition de la Vie" -

- Prix de l'ouvrage :25€ .
- Pour toute commande s'adresser à :

Irène HERPE-LITWIN Secrétaire générale AEIS
39 rue Michel Ange 75016 PARIS
06 07 73 69 75
iherpelitwin@gmail.com

L'ouvrage cité ci-dessus est accessible gratuitement (open access) sur le site d'edp sciences:

http://www.edp-open.org/images/stories/books/fulldl/Formation-des-systemes-stellaires-et-planetaires.pdf

Documents

En complément de la conférence d'Alexeï GRINBAUM nous vous proposons :

p. 7: Un article d'Alexeï GRINBAUM publié le 12 février 2016 dans la revue arXiv:1512.01035vE intitulé: "How device-independant approaches change the meaning of physical Theory"

How device-independent approaches change the meaning of physical theory

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Abstract

Dirac sought an interpretation of mathematical formalism in terms of physical entities and Einstein insisted that physics should describe "the real states of the real systems". While Bell inequalities put into question the reality of states, modern device-independent approaches do away with the idea of entities: physical theory may contain no physical systems. Focusing on the correlations between operationally defined inputs and outputs, device-independent methods promote a view more distant from the conventional one than Einstein's 'principle theories' were from 'constructive theories'. On the examples of indefinite causal orders and almost quantum correlations, we ask a puzzling question: if physical theory is not about systems, then what is it about? The answer given by the device-independent models is that physics is about languages. In moving away from the information-theoretic reconstructions of quantum theory, this answer marks a new conceptual development in the foundations of physics.

1 Introduction

Often hailed as a "second quantum revolution" [4], the introduction of correlation inequalities by John Bell [13] inaugurated a conceptual development whose significance took several decades to be fully appreciated. We submit that this revolution reaches a surprising summit with the development of device-independent approaches and model-independent physics, supporting a dramatically new view of physical theory.

Quantum mechanics describes the evolution of a system under a particular Hamiltonian and the results of measurements operated on this system by the observer. The concept of observer is external to the theory. Whatever its physical constitution, the observer's only role is to choose a measurement setting and register the result of the observation: an operational approach. Correlations between the observer's choices and results are intuitively taken to be mediated by information carriers: physical systems. On one view, systems are "lines" or "wires" between "boxes" in symbolic diagrams connecting various operations on the observer's information—a conception that leads to "new modes of explaining physical phenomena" [23, 24, 25]. The old explanatory mode, on the contrary, takes systems to be constituted through separation from non-systems (measurement devices or the environment): a system is a bouquet of relevant degrees of freedom jointly described by a single name. That such a division enables explanation is an idea with a long philosophical history (*διεῖλεν* from *διαιρέω*, Plato *Timaeus* 41d). We argue, firstly, that the old explanatory mode does not apply to device-independent approaches. Secondly, in the new explanatory mode systems become auxiliary concepts and, like any accessory tool, they have limited utility. Still occasionally employed in the literature, they represent little more than a counterintuitive and unhelpful remnant of the old regime. More interestingly, the new explanatory mode frequently produces a physical theory that does not refer to systems at all.

In quantum mechanics, it is assumed that a measurement setting is chosen in earnest, i.e., the observer trusts the system to be constituted of precisely the degrees of freedom described by the theory. What the system is, is known in advance and is correct. For example, if one performs a binary measurement of photon polarization, then one expects *a priori* that the measurement device will indeed measure photons. This trust in preparation devices is usually not subject to theoretical scrutiny, yet it is in principle—and often experimentally—unfounded.

The problem of trust contains a further aspect. If the distinction between a system and a measurement device is fixed within one laboratory, then it is usually taken for granted that all other laboratories, should they come to observe the processes in the first one, will make the same distinction along the same separation line. The identity of the system does not depend on the observer; only its state may vary in relation to the observer's choice of measurement. The "Wigner's friend" gedankenexperiment [65] assumes that different observers will agree on system identification but disagree on state ascriptions. It is understandable that this agreement may be a matter of unassailable trust between friends; it has been put into question and studied mathematically only recently [41, 58].

Absence of trust is a concern that quantum cryptography is designed to address. It has tools for working with systems of "unspecified character" [6] or "unknown nature" [7]. A device-independent approach employs such tools: it is a theoretical investigation performed without relying on the knowledge of the laws governing the systems' behaviour. A conventional 'device' refers here to any process or apparatus described by a theory, whether classical or quantum, which is explicitly designated. This terminology was first introduced by Mayers and Yao [52], who developed device-independent quantum cryptography with imperfect sources. Their suggestion was to render, through a series of tests, an untrusted but "self-checking" source equivalent to an ideal one that can be trusted *a priori.* These tests do not rely on the degrees of freedom pertinent to the system or, to put it differently, on our knowledge of the physical theory that describes their evolution. They only involve inputs and outputs at two separate locations: a device-independent protocol (Section 2). Over the years quantum cryptography has developed an array of such methods for dealing with adversaries which, via action upon sources, effectively turn systems into untrusted entities. Device-independent protocols are important for randomness generation [26, 59], quantum key distribution [8], estimation of the states of unknown systems [7], certification of multipartite entanglement [6], and distrustful cryptography [1].

Some of these cryptographic protocols found a broader use in quantum information, e.g. device-independent tests are performed on Bell inequalities, on the assumption that superluminal signaling is impossible [5], or on the existence of a predefined causal structure (Section 3). But the import of device-independent methods extends even further. Device-independent methods convert the usually implicit trust of the observer into a theoretical problem. By doing so, they erase one of the main dogmas of quantum theory: that it deals with systems. To appreciate the significance of this shift, we compare it with another paradigmatic change captured by Einstein in the form of a distinction between principle and constructive theories (Section 4).

This dramatic shift is not only due to the import of device-independent methods from quantum cryptography into general quantum physics. If these methods have indeed triggered the development, the latter had been prepared by the reconstructions of quantum theory (Section 5). Operational axiomatic approaches to quantum mechanics focus on the inputs and outputs of the observer: a "box" picture. The postulates that successfully constrain the box to behave according to the rules of quantum theory become our best candidates for fundamental principles of Nature. In a device-independent approach, such postulates are also at work: they are the only content of physical theory along with the inputs and the outputs of the parties.

Incompatible with the old explanatory mode, device-independent models typically do not meet the conditions for the emergence of robust theoretical constituents corresponding to real objects. By allowing no room for systems, they inaugurate the obsolescence of this elementary building block: a theory may contain no systems but remain physical. The spread of this view from quantum cryptography to general quantum physics (Figure 1) raises a question of meaning: if physical theory is not about systems, what is it about? This requires a philosophical (Section 6) as well as a mathematical (Section 7) investigation. Device-independent models suggest a possible answer: physical theory is about languages. Not only is such a theory possible; the spread of device-independence shows that it may become routine. Perhaps it indicates the right direction for moving beyond quantum theory.

2 Physics in a box

Device-independent models are defined as a set of n parties, each of which 'selects' a measurement setting or 'places' an input value $x_1 \in \mathcal{X}_1, \dots, x_n \in \mathcal{X}_n$ respectively, and 'subsequently' 'obtains' an output value or a measurement result $a_1 \in \mathcal{A}_1, \dots, a_n \in \mathcal{A}_n$. The sets $\mathcal{X}_1, \dots, \mathcal{X}_n$ and $\mathcal{A}_1, \dots, \mathcal{A}_n$ are alphabets of finite cardinality. The verbs used in these expressions merely convey an operational meaning of the inputs and outputs; they do not imply that any party exercises free will or has conscious decision-making procedures. The term 'subsequently' introduces a local time arrow pointing from each party's input to its output. Although such local time arrows seem quite intuitive, in full generality they need not be assumed either. A fully general setting requires, therefore, that absolutely nothing be postulated about the way inputs are transformed into outputs, except two conditions: a) these two types of data are clearly distinguished;

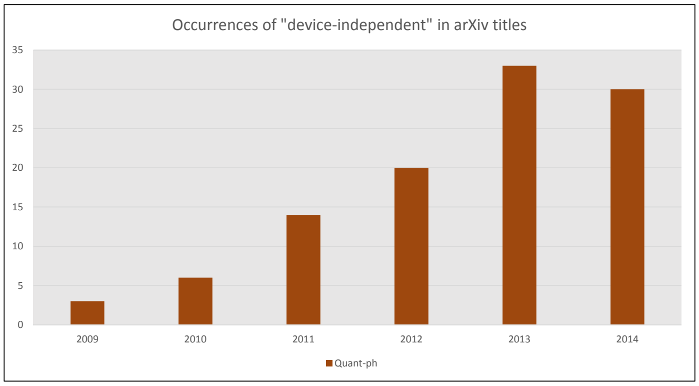

Figure 1: Occurrences of the term “device-independent” in arXiv quant-ph publications.

b) the process of transformation is physical. Physics is contained in the probability distribution $\mathbf{p} = P(a_1, \ldots, a_n|x_1, \ldots, x_n)$ (Figure 2).

All device-independent models studied in the literature introduce further constraints on $\mathbf{p}$. The most frequent one is the no-signalling principle: a choice of measurement by one party must not influence the statistics of the outcomes registered by a different party. Mathematically, the distribution $\mathbf{p}$ is non-signalling if and only if all one-party marginal probabilities are functions of their respective inputs x_i:

$$P(a_i|x_1, \ldots, x_n) = P(a_i|x_i). \tag{1}$$

Although very common, this assumption is not universal, e.g., when device-

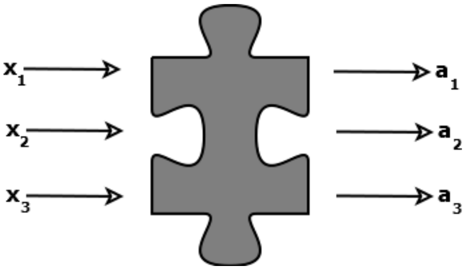

Figure 2: In the case of $n = 3$ parties, physics is fully contained in the probabilities $\mathbf{p} = P(a_1 a_2 a_3|x_1 x_2 x_3)$.

independent methods are used to test general causal inequalities, the impossibility of so called one-way signalling is not a prerequisite [9].

It is possible to argue that the property of device-independence was already apparent in Bell's own formulation of his inequalities [13]. However, the first proper *model* featuring non-signalling and device-independence is to be found in the work of Popescu and Rohrlich [61]. A non-local, or Popescu-Rohrlich (PR), box describes unknown processes which connect the inputs $x, y \in \{0, 1\}$ and the outputs $a, b \in \{0, 1\}$ of two parties according to the joint distribution

$$P(ab|xy) = \begin{cases} 1/2: & a + b = xy \mod 2 \\ 0: & \text{otherwise.} \end{cases}$$

The no-signalling constraint implies that, while a PR-box is designed to go beyond quantum theory, it nevertheless respects the laws of special relativity. Its device-independent non-local structure accommodates a violation of the Tsirelson bound [22] by reaching the maximum amount of correlations in the CHSH inequality. Since PR-boxes allow for more-than-quantum (often called *postquantum*) correlations, they cannot be built experimentally given the current state of knowledge. However, there exist experimental approximations with the no-signalling condition weakened through a coordinated choice of measurement settings [43, 63] or postselection [50].

Hailed as a "very important recent development" [60], device-independent models are characterized by the absence of assumptions about the internal workings of the box. Its 'interior' is not described by a particular physical theory. The box is unknown territory which, since it is assumed to be of interest for physical theory, is also a territory of science. The entire setup belongs within the boundaries of physics (the workings of the box are not miracles) and, at the same time, it opens a possibility to redefine these very boundaries. It may be the case that **p** is consistent with the predictions of an available physical theory, but if this is not so, then the meaning of physical theory is appropriately widened to include the correlations realized by the box.

3 Example: Causal orders

No-signalling is the most commonly used condition on **p**. Other, usually more concrete examples are also formulated as information-theoretic constraints, e.g., a condition on the security of bit commitment [1]. While they take the box closer to quantum theory, such assumptions still leave enough room for models beyond quantum mechanics, giving quantum theory a place in a broader landscape. Research on 'indefinite causal orders' does not rely on a constraint on **p** imported from quantum communication. It explores another surprising feature of device-independence: the absence of global temporal order between the inputs and the outputs associated with different parties. Each party, for sure, can draw an arrow pointing from its input to its output, the latter always succeeding the former in this party's local frame of reference. While such local time axes are well-defined, Chiribella [21] following Hardy [45, 46] suggested that there

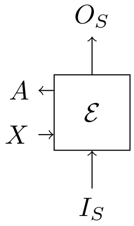

Figure 3: A party is fully defined by the input variable X and the output variable A linked by the map $\mathcal{E}$. The theory does not require any mention of a physical system S that is first received from the environment and then returned to it. Adopted with modifications from [10].

may not be a global notion of time. His work pursued a device-dependent approach, whereby local transformations were taken to be quantum but the big Hilbert space of all parties contained no information on causal relations among them. A mathematical formalism called process matrix was introduced by Oreshkov, Costa and Brukner to deal with such situations [56], leading to a set of further studies [2, 17, 18, 3, 47, 12, 35].

In a device-independent approach, a party is defined, not by a local Hilbert space, but by two random variables: an input X and an output A, and a map $\mathcal{E}$ between them. It is conventional among authors to mention "a physical system S that a party receives from the environment and a physical system that is returned to the environment" [10] and to adduce it to the transformation $\mathcal{E}$ (Figure 3). This is not due to any theoretical necessity: the language merely appends an interpretation of the mathematical formalism. Three strange consequences follow. Taken together, they indicate that the notion of system is not a fundamental ingredient of the device-independent model of indefinite causal orders.

First, the assumption about a physical system first entering, then leaving the laboratory can be rephrased as a condition that each party interacts with the 'environment' or the 'physical medium' only once:

> [Alice and Bob] both open their lab, let some physical system in, interact with it and send a physical system out, only once during each run of the experiment. [15]

The notion of environment here involved is a peculiar one. Described as a whole by the process matrix, it lies outside space-time. 'Environment' is used as a name for a holistic atemporal medium said to supply a system to a party. According to the old explanatory mode of physics, a system is to be constituted through separation from the environment; however, no separation is possible from this one. If the relevant degrees of freedom could be divided from the irrelevant ones in this 'environment', then the degrees of freedom pertaining to the system would remain identifiable as such throughout the experiment. The idea of maintaining (*συνέχοντος*) this separation, or holding together (*συνάγοντος*) the degrees of freedom that constitute the system, is key to providing cohesion (*συγκρατοῦντος*) of whatever is separated or divided from something else (Numenius 4b).

This is a temporal idea, at least for the time of the experiment: if a system melts down, or is broken up, or gets absorbed inside the laboratory, then it ceases to be. The 'holding together' of the degrees of freedom happens in the laboratory's time, but this local time arrow does not extend to the holistic environment described by the process matrix. The latter is not in space-time, hence the impossibility to use a global medium to maintain separation outside the lab, or to maintain anything *tout court*. As a result, the framework of indefinite causal orders cannot accommodate a notion of system which 'enters' or 'leaves' the lab from the environment.

Second, in some circumstances, 'systems' in the process matrix framework may 'enter' the same local laboratory twice: a situation that never occurs to a physical object. Third, both quantum bipartite and classical multipartite processes without predefined causal order are logically consistent and therefore allowed by the theory [11]. Causal correlations between the inputs and the outputs form a polytope that lies in a larger, logically consistent set that includes non-causal correlations. The latter can be shown to violate a causal inequality: an analog of Bell inequality that permits to distinguish between mixtures of predefined causal orders and its genuine absence. In the quantum framework, violations arise already with two parties [56]. With three or more parties, it becomes possible to reach a non-causal point in the larger polytope using only classical probability theory [12]. This is a surprising finding, implying that even a classical device-independent framework cannot always be interpreted as a description of physical systems entering and leaving the laboratories.

These three reasons underscore the difficulty to employ the notion of system in a device-independent approach. Another line of research gives weight to this conclusion by addressing the following point: if a system 'traverses' the laboratory 'from' the input 'towards' the output, one should be able to tell its history, i.e., provide a list of events that occurred to the system in the laboratory. It is, however, impossible; the most radical manifestation of which is the "quantum liar" paradox [33]. Based on postselection, this example showcases a paradoxical conclusion that a future measurement may take an active part in the formulation of the system's past history. Thus, a nearly automatic phrase: "a system is prepared at the start of an experiment," if taken seriously, produces an array of counterintuitive consequences. This phrase may best be abandoned.

Three versions of the same condition pertaining to experimental investigation each characterize a particular aspect of physics.

a) To underline the instrumental or the operational aspect, one chooses as a primitive a unique run of the experiment fully described by an input and an output.

b) To put an emphasis on theory as opposed to experiment, the parties (or the laboratories) are defined, not by spatial arrangements of instruments, but by an input and an output.

c) On the interpretational side, it is commonly assumed that a physical system enters a laboratory and then leaves it.

While they seem complementary, these three different readings may not be equally necessary. The instrumentalism of a) takes a fast route to establishing the mathematical formalism of physical theory. It is then sufficient to follow b) for a purely formal investigation as it contains all the information needed for doing calculations. A 'system' in c) is a mere interpretative device that runs into difficulties when brought to light. It is the least necessary assumption and, unable to give a hand conceptually to a) and b), it often becomes counterproductive as it mires the meaning of physical theory. A theory can be provided by a) and b), without c), containing no systems while staying physical.

4 Relation to 'principle theories'

The question of what amounts to a physical theory is usually debated in the light of a well-known distinction, drawn by Einstein in 1919 [30], between constructive and principle theories. A paradigmatic example of principle theories is Einstein's own special theory of relativity: its entire edifice is derived from simple postulates that reflect abstract universal principles of Nature, not the laws of behaviour of a particular kind of matter. As Einstein noted, such principles serve to "narrow the possibilities" [29]. The same 'narrowing of possibilities' is achieved by introducing constraints on $\mathbf{p}$ in the device-independent approach. This suggests a possible link between the meaning of the latter and Einstein's distinction.

Special relativity is not a constructive theory, i.e., it remains mute on the issue of material constitution of the rods and clocks that act as its measurement devices. Einstein believed that this lack of constructivity was a disadvantage and, consequently, principle theories did not offer a satisfactory understanding of physics [16]. He kept hoping that a constructive theory could provide a better understanding of Nature: "When we say we have succeeded in understanding a group of natural processes, we invariably mean that a constructive theory has been found which covers the processes in question" [30]. But Einstein's desire to obtain a constructive theory as a replacement of his principle-based special relativity never came to be realized. It is tempting to speculate that device-dependent physics describing concrete physical systems will follow the same destiny as constructive theories. If, despite Einstein's wish, no constructive theory has materialized as a replacement of special relativity, it is not impossible to imagine that our intuitive desire to 'fill the box' with physical systems for the purposes of better explaining physics is as illusory. The device-independent approach might stay as a legitimate way of doing physics, without any need to 'fill the box,' much in the same sense as principle-based special relativity has not been surpassed by any constructive theory.

Device-independent approaches inaugurate a bigger shift from concrete physics than Einstein's principle theories. The latter assume, just as constructive theories do too, that the elementary building blocks of physical theory are physical systems. Constructive theories put a direct emphasis on this assumption as they begin their development from certain elementary material constituents. Theoretical entities are, in this case, mere formal representations of real objects. Principle theories achieve a similar conclusion from the opposite direction, by postulating general principles in order to derive a theory of entities constrained by them. Physical systems are now theoretical constructs to be put in correspondence with the real objects. None of the two types of theories includes a possibility that physical theory may not contain any entities, whether real or theoretical, and may not seek to develop a notion of system. Einstein certainly did not envision such a physical theory, be it principle or constructive. As they reach a new level of abstraction from concrete material reality, device-independent approaches surpass Einstein's view.

5 Relation to the reconstructions of quantum theory

The introduction of principle theories by Einstein and a vision of mathematical physics promoted by the Hilbert program have both contributed to the rise of quantum axiomatics. This line of research began with the proposal of quantum logic by von Neumann and Birkhoff in 1935 [14], showcasing a change in the foundational attitude from a physical enquiry dealing with real objects to a mathematical formalism that only contains theoretical entities. In a departure from the Hilbert space quantum mechanics, von Neumann "made a confession" in a letter to Birkhoff that he did not believe in the Hilbert spaces any more [55]. To describe physical systems in a different way, a correspondence was to be established between measurements and a projective-geometric structure isomorphic to an orthomodular lattice. Several decades of research along these lines in quantum logic yielded multiple proposals for the axioms of quantum theory. Orthodox quantum logic was followed by a reconstruction program focused on the operational meaning of quantum theory [40]. In contrast to the previous, heavily mathematical axioms, reconstructions sought to identify a small set of principles with a clear physical meaning. With no exceptions, these axiomatizations contained a postulate about the subsystems and the composition rule (e.g., in [44]), whose function was to put a limit on the amount of correlations that can be reached by the subsystems. Postulates of this kind reduce the maximally allowed set of bipartite or multipartite correlations down to the quantum bound; this can only be achieved, however, if what needs to be derived is already known. The reconstruction program of quantum theory, therefore, sought to reconstruct an already existing theory.

At the same time, composition rules take extra meaning in a more general device-independent approach that goes beyond reconstruction. Imagine that no subsystems are introduced but only a limit on the correlations. This device-independent setup operates with the inputs and the outputs of the parties while it contains no notion of system. Now the available limit on correlations, acting as a constraint on $\mathbf{p}$, is used to derive the conditions under which a notion of system would become meaningful. Systems emerge, then, as a result of some principles, which are usually formulated in the information-theoretic language. Device-independent approaches drive home the importance of such principles: quantum theory appears as one among several possible information-theoretic models. Its meaning in this context has a fainter connection than even principle theories with the concrete constituents of matter like atoms or particles: information-theoretic device-independent theory does not presuppose any kind of physical system at all.

Should one take quantum theory to be a theory of (a particular kind of) information? Such proposals appeared even before the advent of device-independent methods [19, 39], while the latter give them a mathematical expression. Take the example of the Tsirelson bound [22]. If physics is captured by the probabilities $\mathbf{p}$, then all of quantum physics, including quantum bipartite correlations, must stem from some constraints on $\mathbf{p}$. Available constraints for the derivation of the Tsirelson bound are information-theoretic: a limit on communication complexity [27], non-local computation [49], the possibility of a well-defined classical transition (macroscopic locality) [51], or information causality [57]. Whichever assumption one chooses, a non-trivial result is that quantum mechanics emerges in a purely information-theoretic context. It is legitimate to wonder whether such a theory is still affixed to reality and if yes, in what sense.

6 Relation to realism

In a well-known argument purporting to show incompleteness of quantum mechanics, Einstein proclaimed that quantum theory would be complete if the wavefunction ψ described "the real state of the real system" [31]. While Bell inequalities were used to attack the reality of states, device-independent methods do away with the idea of real systems. It is likely that Einstein did not even contemplate such a possibility. Consider the opening lines of the EPR article:

> Any serious consideration of a physical theory must take into account the distinction between the objective reality, which is independent of any theory, and the physical concepts with which the theory operates. These concepts are intended to correspond with the objective reality, and by means of these concepts we picture this reality to ourselves. [32]

A similar dictum can be found in Dirac's 1930 textbook of quantum mechanics, with 'objective reality' replaced by the less ambitious 'physical entities':

> "The most powerful advance would be to perfect and generalize the mathematical formalism that forms the existing basis of theoretical physics, and after each success in this direction, to try to interpret the new mathematical features in terms of physical entities." [28]

Device-independent approaches render both philosophies obsolete. If a theory contains no notion of system, there is no reason to picture reality as comprised of physical entities. For sure, device-independent physics still informs us about Nature but, in a uniquely radical rejection, it does not support a claim that either Nature or physical theory are constituted of entities. This is more powerful than the widespread withering away of entity realism [37], a statement that physical entities are objectively existing, real things. Systems in the device-independent approach are unnecessary not only for the purposes of interpretation, but also on the theoretical side. They cannot correspond to objective reality because they are absent from the theory. Both in the philosophy of physics and in its mathematics systems are no more a requirement.

Device-independent methods promote a view that is also more powerful and unusual that the rejection of 'naive' realism, which continues to characterize many working physicists. Naive realism is an uninformed form of entity realism stating that the objects of experimental science, think electrons or photons, are real because the empirical work and the laboratory heuristic suggest so. First the wave-particle duality, then Heisenberg's indeterminacy relations and the Kochen-Specker contextuality removed all possibility of a consistent account along these lines. Device-independence runs contrary to the experimental heuristic of naive realists to such extent that achieving it in the laboratory becomes a serious challenge. Boxes are usually built out of known systems like photons, yet no knowledge of such systems can be supposed by the experimenter, or the setup would immediately turn into a device-dependent one. That experimentalists often leave unnoticed minor device-dependent assumptions shows how counter-intuitive device-independent physics can be for a naive realist.

If physical theory is not about systems, it is tempting to say, as hinted in Section 5, that it is about information or a special kind thereof. Not all conceptual problems, however, get solved by this answer. It is deeply enigmatic that a theory of information would be applicable to atoms or elementary particles, yet quantum theory applies to them. If information is a more fundamental substance, does it come in many kinds or varieties? One possibility would be that such types of information are all similar in structure (obeying *the* concept of information, e.g., as defined by Shannon [62]) but vary in the values of some parameters. Another option is to radically distinguish one notion of information (e.g., information that cannot be cloned) from all others [20]. In our view, these conundrums are misleading, because the term 'information' is not required to drive home the point of device-independent approaches. 'What is physical theory about?'—it is only appropriate to search for an answer by looking at the mathematical formalism of device-independent methods. What needs to be understood, therefore, is the common conceptual background of the various mathematical constraints on $\mathbf{p}$. Such a background should become a common philosophical denominator of physics in lieu of Shannon's or von Neumann's information theory.

7 Example: "Almost quantum" correlations

Some constraints on $\mathbf{p}$ allow for an interpretation of the device-independent setup in terms of systems. This *emergence* of systems needs to be demonstrated mathematically, and an important check is the type of composition rule for such emerging entities. Quantum theory describes composition via the tensor product structure. If one now posits that the no-signalling box is described by a global Hilbert space, one needs to test the availability of the tensor product between the subspaces that characterize each party. The work on so called "almost quantum correlations" addresses this question [53, 54].

Remarkably, there is enough leeway between two assumptions: the existence of the global Hilbert space and the tensor product structure of local subspaces. Rather than by the tensor product, the condition of independence of local observables can be captured by commutativity between two families of projectors pertaining to different parties. Correlations exhibited by the models based on commutativity relations differ slightly from quantum correlations: they are "almost" quantum.

The notion of subsystem, and with it the notion of physical system, is put into question in the device-independent models leading to almost quantum correlations. This is apparent in the definitions given by several authors working on this topic. It is not unusual to find a common-sense expression of device-independence in the familiar language of local subsystems:

> Consider a scenario where n parties conduct measurements $\bar{x} = (x_1, \ldots, x_n)$ on *their respective subsystems*, obtaining outcomes $\bar{a} = (a_1, \ldots, a_n)$. [54, our emphasis]

The notion of subsystem involved is, however, different from the usual one. Rigorously speaking, it has to be defined algebraically:

> Subsystems are defined by specifying observable algebras: these are assumed to be C^*-algebras that mutually commute. [38]

According to common sense, this algebraic definition must be a mere rephrasing of the usual Hilbert space notion. To check this, one appeals to the composition rule. It transpires that the result of this check is negative: the notion of subsystem in the sense of commutativity of subalgebras does not correspond to the usual idea of physical systems that are statistically independent [36]. Fritz formulates a conceptual lesson:

> It is our point of view that the operation of forming a composite system $\mathcal{H}_A \otimes \mathcal{H}_B$ from its subsystems $\mathcal{H}_A$ and $\mathcal{H}_B$ should not be a fundamental structure in a physical theory. The point is that nature presents us with a huge quantum systems which we observe and conduct experiemnts on, and in some ways this total system behaves as if it were composed of smaller parts. Hence it seems that the correct question would be "When does a physical system behave like it were composed of smaller parts?" rather than "How do physical systems compose to composite system?". Note that this is in stark contrast to many other approaches to the foundations of quantum theory, in which the operation of forming a composite system from subsystems is a fundamental structure. [38]

Thus systems in the framework of almost quantum correlations do not obey ordinary intuition. Even if, as in this example, the new mode of explaining physical phenomena occasionally refers to systems, one must remain aware of the pitfalls. A common-sense notion of system is clearly unhelpful, yet it is no accident that the authors strongly desire that their framework be explanatory of physics: “The ubiquity of the almost quantum set $\tilde{Q}$ [...] seems to suggest that it emerges from a reasonable (yet unknown) *physical* theory” [54, our emphasis]. The device-independent approach enjoys the full rights of a physical theory. If such future theory cannot be a theory of physical systems, what would it be a theory of? One finds a tentative answer in a definition using only the strictly necessary concepts:

> For Alice (respectively for Bob), an experiment is a process or black box to which she feeds an input x from the alphabet $\mathcal{X}$ and from which she receives an output a from the alphabet $\mathcal{A}$. Alphabets $\mathcal{X}, \mathcal{Y}, \mathcal{A}, \mathcal{B}$ are of finite cardinality. [48]

This suggests that physical theory is about languages or a special kind thereof. It is characterized by a choice of alphabets for the inputs and the outputs and by the conditions imposed on this linguistic structure. Strings or words in such alphabets form a common mathematical background of device-independent approaches.

In physical theory strings or words are given semantics as input-output records, but, as in Shannon’s theory, they can also be studied purely formally. The imposed constrains limit the set of all possible strings and enable the use of probability calculus. This, in turn, can be interpreted as a prediction of measurement results, or an update of the observer’s information, or emergent causal relations between events, or a mere correlation between certain inputs and ensuing outcomes. The choice of interpretation has no bearing on the main point: mathematically, device-independent approaches are based on strings. Geometric structures, e.g., the Hilbert space of quantum theory, tend to be device-dependent; in a device-independent approach, they are replaced in the fundamental position by a linguistic structure.

The observer’s description based on a set of words in a formal language can be traced historically to Everett and Zurek [42]. Everett argued that observers are characterized by their memory, i.e., “parts... whose states are in correspondence with past experience” [34]. Zurek suggested that algorithmic randomness of available information be added to physical entropy [67, 66]. Both refer, explicitly or implicitly, to strings. An interpretation conceptually limited to this basic mathematical ingredient of device-independence provides a common philosophical denominator of device-independent physics. While this approach gives an unusual answer to the problem of meaning of physical theory, it is more sound that a seemingly straightforward interpretation in terms of systems. It only relies on what is given by the mathematics of the theory; an alternative reading using the notion of system would add further concepts that are remnants of the old explanatory mode. Last but not least, a statement that “physical theory is based on languages” is more amenable to mathematical analysis that the vaguer “physics is about information.”

8 Conclusion

In quantum cryptography, it has always been allowed, even customary, to ask the anathema question of physical theory: what if a preparation or a measurement device is cheating on the experimenter? Is it still possible to obtain meaningful results? Under the influence of cryptography, quantum theory developed a way of doing physics that can accommodate such questions: a device-independent approach. Conceptually, device-independence does not require that the notion of system be present in physical theory. It is then legitimate to ask what such a new physical theory is about. Device-independent models of indefinite causal orders and almost quantum correlations suggest a possible answer: it is about languages. Like information-theoretic postulates that lead to the derivation of quantum theory in the operational framework, particular constraints on languages produce a device-independent model that exhibits characteristic features of quantum theory. Further consequences of this novel view of physical theory remain to be explored both conceptually and mathematically.

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