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ORIGINAL RESEARCH

How to Conceptual Engineer 'Entropy' and 'Information'

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Abstract

In this paper I discuss how to conceptual engineer 'entropy' and 'information' as they are used in information theory and statistical mechanics. Initially, I evaluate the extent to which the all-pervasive entangled use of entropy and information notions can be somehow defective in these domains, such as being meaningless or generating confusion. Then, I assess the main ameliorative strategies to improve this defective conceptual practice. The first strategy is to substitute the terms 'entropy' and 'information' by non-loaded terms, as it was first argued by Bar-Hillel in the 1950s. A second strategy is to prescribe how these terms should be correctly used to be meaningful, as it was pioneered by Carnap (Two essays on entropy, University of California Press, 1977) in *Two Essays on Entropy*. However, the actual implementation of these two ameliorative strategies has been historically unsuccessful due to the low credentials that philosophers as conceptual prescribers have among scientists. Finally, to try to solve these obstacles, I propose a third strategy based on leveraging evidence from the contribution of philosophy as a complementary science or the so-called 'Philosophy in Science' (à la Pradeu et al. in Brit J Philos Sci 75:(2):375–416, 2024) to integrate conceptual prescriptions and analyses of entropy and information as part of the scientific practices in which these notions are used.

> *"I admit that the temptation to identify these measures is great and almost irresistible when the 'information' terminology is used. But the identification is still a mistake, and the fact that this mistake was made by many competent thinkers only increases its seriousness and the necessity of a complete clarification of the situation" (Bar-Hillel 1955, 287)*

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1 Introduction

It goes without saying that entropy and information have been two of the most problematic concepts in the recent history of scientific ideas. However, it is important to understand how these two concepts can be problematic. In the case of social concepts such as RACE or GENDER, it is clear that they can be problematic insofar as a faulty notion (e.g., using 'race' to segment the human population into groups for biological reasons) directly affects our everyday reality. In the context of scientific and engineering disciplines, the deficient use of terms such as 'entropy' or 'information' can have tangible consequences.[1] For instance, a significant portion of the scientific community has devoted nearly a century to debating issues that are ultimately futile for generating knowledge or being directly applicable. Despite the numerous calls to action from scientists (e.g., Denbigh, 1981; Wicken, 1987), it has been precisely the philosophers of science who have devoted the majority of their efforts since the early 1950s to finding a solution to this conceptual problem. These solutions would be encompassed within what in the metaphilosophical literature is called 'conceptual engineering' (Cappelen, 2018; Isaac et al., 2022), which can be defined as the method of attempting to improve our conceptual practices.

However, it is not yet evident which engineering approach would be most effective to improve the conceptual practices linked to the use of 'entropy' and 'information'. As will be argued, the most prevalent strategy has been the terminological substitution of 'entropy' and 'information' with alternative terms in disciplines where conceptual deficiencies arise (e.g., Bar-Hillel, 1955; Wicken, 1987; Ben-Naim, 2008). As soon as the early-1950s, Rudolf Carnap and Bar-Hillel, (1952 [1977]) also attempted to resolve this ill-defined problem by relying on an engineering method he called *explication* (see Brun, 2016). His solution was not to change terms, but to prescribe that entropy should not be used or interpreted as a measure of the observer's information, as popularized in the 1950s by Brillouin (1962) and Jaynes (1957), but as a notion defined on measurable properties to become physically significant. Although both conceptual engineering strategies initially appeared promising, in this paper we argue that their failure can be attributed to a number of historical factors. These include the high pursuit-worthy expectations generated by their prospective applications, the rapid and historically prolonged (1950–2024) settlement of such concepts, the low authority of philosophers to prescribe conceptual uses to scientists, and so on. In order to avoid these obstacles, we will propose a third strategy that does not entail a particular improvement (change of terms, prescription of use, etc.). Instead, it will rely on leveraging evidence of philosophical contributions in science to foster the required socio-epistemic conditions that would allow the effective implementation of local ameliorative conceptual solutions in the community of entropy-information users.

The plan for the paper is the following. Firstly, we introduce conceptual engineering (specifically for those who are unaware of the recent metaphilosophical literature) as a general method aimed at improving the way in which we use some concepts. In Sect. 3, we describe the manner in which the concepts of entropy and information became

[1] As it is conventionally accepted in the literature, here we will use small capitals for concepts (e.g., RACE) and simple quotations marks for linguistic expressions (e.g., 'race') as conceptual vehicles.

intertwined after the popularization of Shannon's information theory, as well as in the information-theoretical reformulations of statistical mechanics in the 1950s. Subsequently, we assess (Sect. 4) the many conceptual flaws that arise from the continued, pervasive intertwining of the terms 'entropy' and 'information'. Section 5 will be devoted to evaluating the most frequent conceptual engineering strategy in this domain: the replacement of a deficient terminology with a non-deficient one. A second engineering strategy, paradigmatically pioneered by Carnap and Bar-Hillel, (1952 [1977]), will be evaluated in Sect. 6. This strategy involves prescribing how entropy (and information) concepts should be used. Finally, in Sect. 7, we will present a novel engineering strategy that focuses on the effective implementation of the process of conceptually analyzing entropy and information as part of the scientific practices in which those notions are used. Let us begin by elucidating what is meant by conceptual engineering.

2 What is Conceptual Engineering?

Conceptual engineering is the philosophical method that allows us to evaluate and subsequently improve our concepts. Although it has gained momentum in recent years in the philosophical literature, authors such as Thomasson (2020, p. 2) argue that conceptual engineering is a practice that philosophers have been doing since ever, or at least explicitly since almost eight decades ago with Carnap's explication method. One might even posit that this procedure is also carried out in non-philosophical domains such as the sciences, policy-making or legal practices. Thus, the Department of Social Services of the Australian Government engineers the ordinary concept of CONSENT by stating that it should be applied only to relationships that are (i) free and voluntary, (ii) informed, (iii) affirmative and communicated, etc.[2] In the context of philosophy, conceptual engineering is usually distinguished from other concept-based methods such as descriptive conceptual analysis is its aim of improving the functionality of a pre-existing concept (Nado, 2021) to achieve goals such as promoting social equality, a better understanding of current society, or solving a theoretical problem. As paradigmatic cases, Haslanger (2000) engineered the meaning of the term 'woman' through a redefinition with the straightforward aim of promoting the use of a fairer concept of WOMAN, while Scharp (2013) sought to improve the ordinary notion of TRUTH to avoid paradoxes when analyzing the semantics of natural languages. This is why the evaluative and improvement component of this method is of central importance (Isaac et al., 2022).

However, there is considerable disagreement regarding the fundamental aspects of this activity. The initial point of contention in this regard is on what type of object is being engineered. In accordance with the recent taxonomy proposed by Isaac et al. (2022) and considering cognitive-linguistic and semantic-pragmatic parameters, the thing that is being engineered can be classified as: (a) a concept understood philosophically as a broadly-construed semantic object (Fregean sense, Carnapian intension, etc.) that allows us to classify its referents or extensions (e.g., Cappelen, 2018); (b) a concept understood psychologically as a mental structure of information that allows us to make inferences

[2] https://www.dss.gov.au/sexual-consent/the-commonwealth-consent-policy-framework

about the phenomena it refers to (e.g., Machery, 2017); (c) the meaning of a linguistic expression such as 'democracy' (e.g., Cappelen, 2023); (d) the meaning specifically associated with a linguistic user's or speaker's beliefs about what expressions such as 'conspiracy theory' refer to (e.g., Napolitano & Reuter, 2021); or (e) the multiple factors underlying the linguistic rules that regulate the use of linguistic expressions such as 'marriage' (e.g., Löhr 2021). Although these modalities are not mutually exclusive and frequently overlap in literature, distinguishing them will be heuristically useful in clarifying the different levels of engineering that our application case will demand. Consequently, in the interests of clarity and consistency, we will henceforth use the expression 'conceptual vehicle' as a generic term to refer to the object of the engineering process, regardless of the specific context, unless otherwise stated.

Conceptual engineering is also quite diverse in its possible underlying methods. Let us look at four representative examples in this sense. First, one could perform an ordinary language analysis to obtain linguistic data on how expressions are used to assess what is the best strategy to improve a representational vehicle, as Cappelen (2018, 2023) in the case of the expressions 'intuition' and 'democracy'. Second, Scharp (2013) shows that by relying on a logical analysis of the use of terms like 'truth' can contribute to the improvement of their functions. Third, following Machery (2017) or Nado (2021) one can also employ experimental methods to systematically collect data on (i) what the representational vehicle is like (description), (ii) what are its shortcomings to be improved (evaluation), or (iii) what are the best prescriptive strategies (implementation). Fourth, it would be possible to incorporate mathematical and even computational methods, such as natural language processing (NLP) tools to process corpuses of linguistic data or regression techniques in the case of experimental data. This is just a sample of the methodological variety of conceptual engineering.

In addition, we will observe a diversity of approaches with regard to the philosophical domains in which explicit conceptual engineering projects have been conducted: namely, inductive logic (e.g., Carnap & Bar-Hillel, 1952), moral philosophy (e.g., Railton, 1989), feminist and racial philosophy (e.g., Haslanger, 2000), natural language semantics (e.g., Scharp, 2013), epistemology (e.g., Fassio & McKenna, 2015), metaphilosophy (e.g., Cappelen, 2018), political philosophy (e.g., Cappelen, 2023), or even in analytic theology (e.g., Greenough, Forthcoming). As such, any review of the recent literature on conceptual engineering would immediately reveal an important disciplinary asymmetry. While practices of conceptual engineering have flourished in broad disciplines such as practical philosophy (i.e., moral, political, feminist, etc.), they have not yet taken root in other domains such as the philosophy of STEM (science, technology, engineering, and mathematics) areas. It is independently of the reasons why this has been actually the case that we will here intend to demonstrate the considerable utility of conceptual engineering,[3] not only in the promotion of social justice or the clarification of logical-epistemological

[3] A plausible sociological explanation for this disciplinary asymmetry is as follows: general philosophers are not generally considered or perceived as authorities on how they must use STEM concepts (or what STEM concepts they should use) by STEM practitioners (e.g., scientists, mathematicians, engineers, etc.). In contrast, philosophers could actually be considered as conceptual prescribers for their wide-scope target audiences in case of moral-social issues. Additionally, a conceptual explication can be provided in terms of philosophers assuming that in the STEM, there are no ordinary notions, whether vague, imprecise, or non-functional, to be engineered.

problems, but also by increasing the conceptual quality of our best scientific-technical knowledge.

As already mentioned, this paper aims to conceptual engineering the notions of entropy and information as they are used in some branches of physics, mainly thermodynamics and statistical mechanics, as well as in some engineering and mathematical fields, such as information theory. Similarly to other ameliorative projects (Isaac et al., 2022), our engineering process encompasses four interrelated stages: (i) describing how the terms 'entropy' and 'information' are used in the relevant areas, and how they historically became entangled in 1950s; (ii) evaluating the conceptual flaws entailed by those usages; (iii) assess the main strategies to improve this conceptual practice, and (iv) explore how these improvements could be eventually implemented. Having clarified this point, we now proceed to unfold the descriptive task of our conceptual engineering project.

3 Uses of 'Entropy' and 'Information' in Physics and Information Theory

The term 'entropy' was first coined in 1865 by German physicists Rudolf Clausius to refer to the irreversible dissipation of energy in processes involving transferences of heat Q at an absolute temperature T, then quantifying the degree to which energy becomes unavailable for useful work. Prior to this terminological choice, Clausius had relied on the convoluted expression 'equivalence-value' to refer to the quantity (also called the 'S' function) already defined in his renowned 1854 paper. As a function, 'entropy' was a measure of the mechanical counterpart of heat generated by any engine performing a process, as predicted by the second law of thermodynamics (TD). In the 1865 paper, Clausius justified terminological choice by its lexical resemblance of with the physically significant term 'energy', in turn coined by T. Young in 1807 as a substitute for the then-ubiquitous Latin expression '*vis viva*':

> "I prefer going to the ancient languages for the names of important scientific quantities, so that they mean the same thing in all living tongues. I propose, accordingly, to call S the entropy of a body, after the Greek word 'transformation.' I have designedly coined the word entropy to be similar to energy, for these two quantities are so analogous in their physical significance, that an analogy of denominations seems to be helpful." (Clausius, 1865, quoted by Cooper 1968, 331)

It should be noted that in the context of TD, the term 'entropy' is neither a statistical notion (i.e., not defined using probabilistic tools but differential calculus) nor entails any explicit claim about the microscopic constituents of matter (i.e., it is derived from observable quantities). Nevertheless, the term 'entropy' is also central in the domain of statistical mechanics (SM), a theory devoted to statistically modelling macroscopic behaviors, such as those phenomenologically described by TD. In this SM context, Ludwig Boltzmann and his disciples Paul and Tatiana Ehrenfest redefined 'entropy' as the number (or the probability measure) of equiprobable microscopic configurations of an individual system underlying a particular macroscopic state.[4] J. W. Gibbs also redefined the term 'entropy' for SM context. But, in contrast to Boltzmann's approach, Gibbs' formulation of 'entropy' cannot be applied to individual systems (e.g., a piston, a gas in a box) but to statistical ensembles, namely, an infinite collection of independent systems following the same equations.

The term 'entropy' was also used as the name for a measure in Claude Shannon's (1948) theory of signal transmission or 'information theory' (IT), a novel framework devoted to use advanced statistical tools to improve how messages could be efficiently encoded as well as transmitted in communicative channels that can distort them. Without delving into technical details, the function named 'entropy' in IT measures (as averages quantities of binary units, i.e., 'bits') the degree of unpredictability of a sequence of symbols randomly generated, depending not on what the symbols could possibly mean but rather on their frequencies.[5] Shannon's terminological choice of the term 'entropy' for this IT function is usually explained by recalling the episode reported by Tribus:

> "What's in a name? In the case of Shannon's measure the naming was not accidental. In 1961 one of us (Tribus) asked Shannon what he had thought about when he had finally confirmed his famous measure. Shannon replied: "My greatest concern was what to call it. I thought of calling it 'information,' but the word was overly used, so I decided to call it 'uncertainty.' When I discussed it with John von Neumann, he had a better idea. Von Neumann told me, 'You should call it entropy, for two reasons. In the first place your uncertainty function has been used in statistical mechanics under that name. In the second place, and more important, no one knows what entropy really is, so in a debate you will always have the advantage.'" (Tribus & McIrvine, 1971, 180)

It is noteworthy that the Bell Labs engineer Ralph Hartley (after whom Shannon designated his entropy function as 'H') employed 'information' in a paper 1928 as the name for a function similar to Shannon's. Apart from Shannon's terminological choice, the mathematician John von Neumann contributed to popularizing the perception of a disciplinary continuity between IT and SM. In fact, Warren Weaver, who coauthored Shannon's 1949 book, relied on the authority of von Neumann to argue for the IT sense of 'entropy' as a somehow natural extension of the Boltzmannian SM sense. On a footnote, he famously claimed that: "Dr. Shannon's work roots back, as von Neumann has pointed out, to Boltzmann's observation, in some of his work on statistical physics (1894), that entropy is related to 'missing information', inasmuch as it is related to the number of alternatives which remain possible to a physical system after all the macroscopically observable information concerning it has been recorded" (Weaver, on Shannon & Weaver, 1949, 3, fn.1).

[4] Historically, this now-canonical notion of 'Boltzmann entropy' (also 'Boltzmann coarse-grained entropy') was actually developed by Boltzmann's disciples Paul and Tatiana Ehrenfest circa 1911 (see Uffink 2007).

[5] According to Lombardi et al.: "Shannon entropy is concerned with the statistical properties of a given system and the correlations between the states of two systems, independently of the meaning and any semantic content of those states." (Lombardi 2016, 1984).

The late-1940s usage of the term 'information' by Von Neumann and Weaver to clarify the SM notion of 'entropy' was not a novel one. In fact, almost two decades before Shannon published his 1949 paper, G. N. Lewis already claimed that "gain in entropy always means loss of information, and nothing more" (Lewis, 1930, 577). In contrast to the technical term 'entropy', the mass noun 'information' was not developed by any author to satisfy any specific purpose. In an etymological sense, the English noun 'information' comes from the English verb 'to inform', and this in turn has evolved after centuries of usage from the Latin verb '*informare*', used at least since the Roman empire. Thus, meaning of 'information' has been evolving since then (Capurro & Hjorland, 2003). On a first glance, the term 'information' is used in everyday context to refer to a non-necessarily true semantic content that can provide knowledge and can be transmitted (e.g., Floridi, 2011; Timpson, 2013, 11–19; Adriaans, 2020).[6] Following the early-1950s perception of IT as providing a quantitative measure of information, not merely in communicative contexts but across several scientific disciplines (the so-called 'Shannon's bandwagon', see Shannon (1956) and Kline [2015, Chap. 3]), some physicists in the SM domain attempted to leverage 'information' and related terms to either imbue IT's notion of entropy with physical significance or to reinterpret the SM's concept of entropy.

For example, Léon Brillouin (1962) promoted a non-technical use of the noun 'information' to reinterpret the meaning of (specifically Boltzmannian) SM entropy: "entropy measures the lack of information about the actual structure of the system. This lack of information introduces the possibility of a great variety of microscopically distinct structures, which we are, in practice, unable to distinguish from one another." (Brillouin, 1962, 160). Moreover, he originally coined the term 'negentropy' (a contraction of 'negative entropy') to denote negative quantities of Boltzmann SM entropy, as well as relied on the expression 'bound information' to refer to SM entropy ratios. According to Brillouin proposal, quantities of 'information' and 'entropy' defined in SM context are inversely proportional,[7] so that "Increase of entropy and loss of information proceed together [in macroscopic processes such a gas expansion in a box]" (Ibid., 157). Finally, Brillouin exploited those connections to render Shannon's IT use of the term 'entropy' as physically meaningful: "The connection between entropy and information was rediscovered by Shannon, but he defined entropy with a sign opposite to that of the standard thermodynamical definition. Hence what Shannon calls entropy of information actually represents negentropy." (Ibid., 161).

[6] For representative conceptual analyses of the everyday meaning of 'information' see the following: "Intuitively, [the noun] 'information' is often used to refer to user-independent, declarative (i.e., alethically qualifiable), factual, semantic contents, embedded in physical implementations like books, databases, encyclopedias, websites, television programmes, […] which can variously be produced, collected, and processed." (Floridi 2011, 82) or also "The term 'information' in colloquial speech is currently predominantly used as an abstract mass-noun used to denote any amount of data, code or text that is stored, sent, received or manipulated in any medium." (Adriaans 2020).

[7] "We can express this slightly differently by stating that the entropy measures our lack of knowledge or *lack of detailed information*, since [entropy] (…) gives us a measure for the volume in Γ -space in which the representative point can be found" (Ter Haar 1954, 232. Italics added).

A second promoter of this conceptual intertwining is Edwin Jaynes (1957), who interpreted the technical notions of probability and (specifically Gibbsian) entropy in SM as measuring the lack of information (in the ordinary sense of the term) or the uncertainty of an observer about the actual microscopic configuration of a molecular system: "Our probabilities and the entropies based on them are indeed 'subjective' in the sense that they represent human information. But they are completely 'objective' in the sense that they are determined by the information specified" (Jaynes, 1990, 390). Jaynes developed the so-called 'Maximum Entropy Principle' as an approach to SM (Frigg & Werndl, 2011, 129–130), relying on the formal similarity between the mathematical formulation of Gibbs' and Shannon's entropy. The idea is that, to statistically model a molecular system, one should choose the one probability distribution that maximizes the value of Shannon's IT entropy insofar as it represents the observer's lack of microscopic information about the system.

Seven decades after, this progressive conceptual entanglement in the uses of the terms 'entropy' and 'information' (depicted in Fig. 1 below) is now pervasive in the domain of SM and IT. For instance: "Since information, as well as probability, is a concept associated with the knowledge of observers about an object rather than with the object in itself, thermodynamic notions such as entropy and dissipation have at the microscopic level a subjective aspect" (Balian 2005, 350), also "If one accepts the probabilistic [SM] interpretation of the entropy, and agrees on the meaning of Shannon's information, then the interpretation of the thermodynamic entropy as thermodynamic information becomes inevitable." (Ben-Naim, 2008, xxi) and "the quantity [SM entropy], can be used as a measure of non-randomness, or information, available about systems in the ensemble. This function plays a key role as a measure of information in problems of communication and general 'information theory'" (Reif 2009, 231). This is just a small but representative sample of the vast amount of evidence in support of the entangled usage of 'information' and 'entropy' in SM. Thus, our next task is to evaluate whether those usages are conceptually defective or not.

4 Evaluating the Entangled Use of 'Entropy' and 'Information'

There is a widespread perception that the progressive entanglement in the use of 'entropy' and 'information' in SM and IT during the period 1950–2024 has become a defective conceptual practice in these scientific and engineering fields (e.g., Denbigh, 1981; Earman & Norton, 1999; Shenker, 2020). Interestingly, most of these evaluative judgments in the literature emphasize von Neumann's terminological suggestions to Shannon in 1940–1941 as the main source of these conceptual problems: "In my view von Neumann did science a disservice!" (Denbigh, 1981, 113) or "Shannon accepted the advice of von Neumann. But this advice was unfortunate, and caused a lot of misunderstanding and various mistakes that are still with us." (Shenker 2020, 19). Indeed, the decision to accept von Neumann's suggestion has been one of the factors explaining these problems, but it is not the only one (Anta, 2021). Regardless of how it can be explained, our

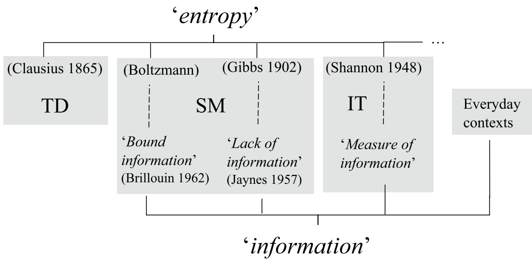

Fig. 1 Conceptual entanglement in the use of 'entropy' and 'information' in SM and IT

task below will be to evaluate each of the main conceptual flaws generated by the intertwined use of 'entropy' and 'information': viz, (i) assuming that 'information' has a physical meaning in SM, (ii) assuming that 'entropy' has a meaning in IT, (iii) conflating the different concepts that are expressed with 'entropy'; and (iv) conflating the different concepts expressed by 'information'.

4.1 The Meaninglessness of 'Information' in Thermodynamics and Statistical Mechanics

On the one hand, one might assume from how the term 'information' is currently used in SM that it has a well-defined physical meaning (or equivalently, that it refers to something in the physical world, or can be correctly applied to describe physical phenomena). In fact, this has been a very extended belief among physicists, as it is usually made explicit in claims such as the following one: "Using information as a fundamental concept makes the understanding of the Second Law much easier. It also removes the mystery that has befogged entropy and the Second Law for a long time" (Ben-Naim, 2008, 251). Nevertheless, there are some reasons to seriously consider that 'information' may have no physical meaning at all when used in the disciplinary domains of TD and SM. First, the everyday sense of 'information' refers to a piece of semantic content that can generate knowledge for an agent. Insofar as semantic, epistemic and agential properties cannot be explicitly formulated within a TD framework, the noun 'information' would have no meaning at all in this phenomenological domain (Earman & Norton, 1999; Timpson, 2013, 11–19). Secondly, the semantic, epistemic and agential properties denoted by using the noun 'information' could be formulated within an SM framework by epistemically interpreting either (i) probabilities, as somehow representing the agent's lack of information about the actual microstate of the molecular system (à la Jaynes, 1957); or (ii) SM entropy quantities, as representing the observer's inability to distinguish which is the actual microstate among all possible ones (à la Brillouin, 1962).

Firstly, the main consequence of adopting an epistemic view on probabilities à la Jaynes is that "On his [Jaynes'] view, SM is about our knowledge of the world, not about the world" (Frigg & Werndl, 2011, 129; Parker, 2011), so that the noun 'information' would immediately cease to have any physical meaning whatsoever in this domain. Because of this, it should be remarked that this source of entanglement between the concepts of 'information' and SM senses of 'entropy' arises exclusively in the subjectivist interpretation of SM-probabilities, wherein probability values represent agent's informational states (beliefs, credentials, etc.) but not physical ones. Apart from Jaynes (1957), subjectivist positions have been popular in the past six decades (e.g., Krylov, 1979; Mackey, 1989; Garibyan and Tegmark, 2014), but they are not universally accepted. In this sense, if SM-probabilities actually reflect an ontic state (e.g., Callender, 1999; Goldstein et al., 2020), then it would make no sense to include the agent's information when modelling the target system.

But even if we don't directly subscribe to a subjectivist or epistemic view on SM-probabilities à la Jaynes, one could still follow Brillouin interpret SM entropy as a measure of information. As was criticized by Denbigh (1981, 112–115) and similarly by Earman and Norton (1999, 9), what Brillouin (1957) actually did in his proposal was using the term 'information' to merely relabeling negative quantities of SM entropy (e.g., S_0-S_1 or -S_B). Their main point was that the agential, semantic and epistemic properties that one intuitively might attach to the term 'information' would play no role whatsoever in fixing SM entropy quantities, therefore Brillouin's informational interpretation is more a terminological ornament than a physically meaningful reconceptualization of SM entropy. Secondly, suppose we use 'information' in Shannon's (1948) technical sense, as a property measurable by its entropy function in terms of the average number of bits required to encode a message to be transmitted to a receiver. But this use would only make sense in a TD or SM framework if one can effectively reformulate the model of signal transmission (messages, sender, receiver, channel, noise, etc.) in the vocabulary of both theories. This immediately excludes TD, since Shannon entropy is an intrinsically probabilistic notion and TD as a discipline does not include probabilistic elements at all. This is what Wüthrich (2017) said in this regard:

> "information, arguably, is an inadmissible concept in fundamental physics. For there to be information in the first place, there must be a communication system in place, a physical set-up such that the concept of information is applicable. In Shannon's mathematical theory of communication (Shannon, 1948), for there to be communication, there must be an information source of a message, a transmitter sending a signal, via a potentially noisy channel, to a receiver, which receives the signal and decodes it for the destination. (…) Even subtracting the intentionality, and abstracting from the personhood of the destination, we are still left with an ineliminable minimum level of complexity required for the signal to be interpreted as the transmission of information" (Wüthrich, 2017, 14)

In the specific case of SM, one could exploit their similarities between IT and SM to interpret the (communicative) space of all possible messages over which Shannon entropy can be defined as a (physical) space of possible microscopic configurations,[8] but as Wüthrich (2017) claimed in the above quotations, IT notions such as 'sender', 'receiver', or 'signal' would play no role in picking up a physical extension (Lombardi et al., 2016, 2001–2003; Shenker, 2020, 20).[9] In Wicken's words: "There is no real information relevant to thermodynamics beyond that provided by the macroscopic state specification." (Wicken 1987, 192). Thus, we have plenty of sound reasons to believe that the term 'information' may not have a non-trivial meaning in TD/SM.

4.2 The Meaninglessness of 'Entropy' in Information Theory

On the other hand, several authors argue that the term 'entropy' is not meaningful when used in the context of IT. Initially, some (e.g., Ben-Naim, 2008) defend that the term 'entropy' coined by Clausius is insignificant even in the domain of TD: "By doing this [Clausius coining 'entropy'], rather than extracting a name from the body of the current language (say: lost heat), he succeeded in coining a word that meant the same thing to everybody: nothing." (Cooper 1968, 331). However, there is now a consensus in the literature that it is the use of 'entropy' in TD that determines what the meaning of this term is (see Uffink, 2007; Frigg & Werndl, 2011). Thus, for 'entropy' to mean anything in the context of IT, it must rely on the very same referential mechanism as in TD: "The term 'entropy' had already been given a well-established physical meaning in thermodynamics, and it remains to be seen under what conditions, if any, thermodynamic entropy and information are mutually inconvertible." (Denbigh, 1981, 113). There are several argument in the literature supporting that this is actually not possible. The first argument is that, if by its definition in TD (Clausius, 1865), 'entropy' refers to a physical quantity that changes in accordance with observable quantities such as volume V or temperature T, the IT use of 'entropy' is independent of the value of these observable quantities, since it depends only on the number of bits required to specify a microstate (Denbigh, 1981). The second argument is that the IT use of 'entropy' is insensitive to the thermal macroscopic behaviors of molecular systems. As Wicken (1987) argues, if the meaning of 'entropy' in IT were constrained by the second law as in TD, then any source of information would tend to increase the entropy generated by the messages we receive, but this is obviously not the case (e.g., it would entail that someone

[8] A nice attempt in this regard is the following: "If we want to characterize [a physical SM] systems in terms of Shannon's H we need to calculate the relevant notion of probability: Shannon's p_i are not transition probabilities, but can be derived from the transitions probabilities as follows. The total probability p_{i} for producing the symbol i can be the combination of all the probabilities of producing it in all possible circumstances; and the physical realization of this might be that the total probability p_{i} of macrostate $_{\mathrm{i}}$ should be given by the sum of the probabilities of arriving in that macrostate from all the other macrostates, within a given time interval. It may be convenient to characterize systems that realize information sources in terms of Shannon's H function in this way." (Shenker 2020, 20).

[9] Of course, one could simply assume that 'information' is meaningful is TD or SM simply because the so-called Landauer's principle (i.e., the idea the erasure of one bit of information necessarily entails an increase of 0.69 K/J of entropy) is actually true. Nevertheless, the theoretical validity of this idea is arguable (e.g., Norton 2013), and there is experimental evidence both confirming and disconfirming it (e.g., Ladyman 2018).

would receive more low-entropy WhatsApp messages like '*Hello!*' in the morning as well as high-entropy texts like '*xxzw*' in the night). Therefore, there are many good reasons to believe that the term 'entropy' cannot be meaningful when used in IT.

4.3 The Confusion of Entropy Concepts in Statistical Mechanics and Information Theory

Another of the main problems arising from the now entangled use of 'information' and 'entropy' in SM and IT is that it has historically fostered (and still does) confusion between the different concepts expressed by these terms. First, Shannon's choice of 'entropy' as the name of his IT measure has fostered several forms of confusion with Clausius' TD entropy, and Boltzmannian or Gibbsian SM entropy. Thus, many scientist have warned that "the use of the word 'entropy' should not lead to confusion of the mathematical concept defined here with the physical concept of thermodynamic entropy." (Jauch & Báron, 1972, 229). But apart from the name 'entropy', the function defined by Shannon (1948) is also formally identical (except for its logarithmic bases and the Boltzmann constant k) to the mathematical expression of the Gibbs entropy (Frigg & Werndl, 2011, 129), which has been widely considered as evidence of the identification between the two concepts. Today, it is easy to find explicit samples of how widespread this identification is in the SM and IT disciplines: "I believe that the entropy is identical, both conceptually and formally, with Shannon's measure of information" (Ben-Naim, 2008, 30). Of course, one can no justify to identify Shannon's and Gibbsian entropy notions simply on the ground of their conceptual vehicles being formally similar. In fact, these two cannot even be correctly applied to the same set of phenomena. You can use Shannon's notion to talk about the 'entropy' of an English text, but not Gibbs, since for you to be able to correctly use 'entropy' in the SM sense you would previously need to compute the average pressure, volume or temperature of that English text.[10] Denbigh made this point crystal clear: "There are, of course, good mathematical reasons why information theory and statistical mechanics both require functions having the same formal structure. They have a common origin in probability theory, and they also need to satisfy certain common requirements such as additivity. Yet, this formal similarity does not imply that the functions necessarily signify or represent the same concepts." (Denbigh, 1981, 113).[11]

[10] "The formal identity of the Shannon and Boltzmann equations results from general demands on the properties of a "state" (…) Whereas [SM entropy] is based on the variety of alternative microstates among which the system moves, [IT entropy] is based on states as events deriving from choices. Since a symbol set, such as a die, expresses alternatives, it becomes tempting to talk about the sequences so generated as 'possessing' entropies" (Wicken 1987, 184).

[11] Other comment in this direction is the following by Ladyman and Ross: "Is the syntactic identity of von Neumann[-Gibbs]-Shannon–Weaver entropy really evidence of anything physical?" (Ladyman and Ross 2007, 216).

4.4 The Confusion of Information Concepts in Statistical Mechanics and Information Theory

Finally, the widespread assumption that Shannon's IT entropy measures 'information' has also led to the confusion between different concepts of information in fields such as SM and IT. The most common confusion is between the technical use of 'information' in IT and the way 'information' is used on a daily basis. That is, while Shannon's concept was quantitatively defined asemantically (i.e., independent of the meaning of messages) and statistically (i.e., based on bit averages), the term 'information' is ordinarily used imprecisely but also as being a semantic, non-statistical and agent-based concept (related to the notions of 'meaning' or 'knowledge'). Or to put it another way:

> "It is worth emphasizing that [Shannon's] is a technical conception of information, which should not be taken as an analysis of the various senses of 'information' in ordinary discourse. In ordinary discourse, information is often equated with knowledge, propositional content, or meaning. Hence 'information' is a property of a single message. But information, as understood in information theory, is not concerned with individual messages and their content; its focus is on all messages a source could possibly send. What makes a single message informative is not its meaning but the fact that it has been selected from a set of possible messages." (Frigg & Werndl, 2011, 119)

This confusion between the ordinary and the technical IT sense of 'information' that caused the popularization of Shannon's theory in the early 1950s also generalized to the physical realm of SM. Let us look at this statement: "our information about an isolated system can never decrease (only by measurement can new information be obtained) (…) the entropy of information theory is (…) a straightforward generalization of the entropy concept of statistical mechanics" (Rothstein, 1952, 90). Here we observe how Rothstein first uses the term 'information' in the ordinary sense as a semantic and agential concept applicable to an observer (i.e., "our information about an isolated system"), and then mentions Shannon's asemantic notion, somehow attributing to it a semantic character that was not originally attributed to it by Shannon.[12] This confusion between the two senses of 'information' derived from the entangled use of this notion and 'entropy' (as well as an epistemic interpretation of the latter) is today all-pervasive in SM, for instance: "the measure of 'information' as defined by Shannon also retains some of the flavor of the meaning of information as we use in everyday life." (Ben-Naim, 2008, 17). Furthermore, recently some authors such as Shenker (2020) have also argued that the intuition driven by

[12] "Shannon's theory, taken in itself, is purely quantitative: it ignores any issue related to informational content. Shannon information is not a semantic item: semantic items, such as meaning, reference or representation, are not amenable of quantification." (Lombardi et al. 2016b).

an ordinary use of the noun 'information' is not just epistemically unfruitful but also misleading in SM.[13]

Finally, we conclude this section by strongly emphasizing that the entropy-information conceptual entanglement cannot be simply understood as a terminological or linguistic issue, as far as it entails a manifold of substantive problems in fields like SM or IT. But, in which sense are these problems substantive? Illustratively, interpreting the notion Gibbs entropy as a quantitative measure of our lack of information about the system's actual microscopic structure can straightforwardly lead to assigning wrong values of TD entropy, as was recently shown inGoldstein et al. (2020),[14] and thus incorrectly describing or modelling the target system under inquiry. This example shows how the entropy-informational conceptual entanglement can lead to substantive problems, such as affecting significatively the results obtained in actual statistical mechanical practices. It is precisely for this reason that the search for plausible ameliorative strategies is an urgent task.

5 Ameliorative Strategy A: Linguistic Negotiation and Terminological Changes

After assessing the main flaws resulting from the entangled uses of 'entropy' and 'information' in SM and IT, we now focus on analyzing the main strategies aimed at ameliorating these conceptual problems that have been proposed since the 1950s. The first strategy aimed at improving this defective conceptual practice is to substitute the terms underlying these conceptual problems by new ones created *ex novo* or giving new use to already existing terms. In this case, the ameliorative procedure would be reduced to a simple terminological change. This solution is close to what has been recently called in the literature 'linguistic negotiation' (Ludlow, 2014) or 'metalinguistics' (Plunkett & Sundell, 2013), where it is assumed that the consensual introduction of a novel terminology in a community of speakers-users (in our case, SM's physicists or IT's technicians) would eventually allow better control over the concepts used in that domain.

The first explicit promoter of this terminology-change strategy was the logician and linguist Yehoshua Bar-Hillel, who in his 1955 article 'An Examination of Information Theory' attributed the problems noted in Sect. 4 to the widespread

[13] "It is often believed that turning to intuitions behind the notion of 'information' makes it easier to explain the concepts of probability and entropy in statistical mechanics. We have illustrated that this is not the case, and that bringing in these intuitions may be misleading and lead to confusions." (Shenker 2020, 23).

[14] Their argument was the following: "For example, suppose an isolated room contains a battery-powered heater, and we do not know whether it is on or off. If it is on, then after ten minutes the air will be hot, the battery empty, and the entropy of the room has a high value S_3. Not so if the heater is off, then the entropy has the low initial value $S_1 < S_3$. In view of our ignorance, we may attribute a subjective probability of 50 percent to each of "on" and "off." After ten minutes, our subjective distribution ρ over phase space will be spread over two regions with macroscopically different phase points, and its Gibbs entropy $S_G(\rho)$ will have a value S_2 between S_1 and S_3 (in fact, slightly above the average of S_1 and S_3). But the correct thermodynamic value is not S_2, it is either S_1 (if the heater was off) or S_3 (if the heater was on). So subjective entropy yields the wrong value." (Goldstein et al., 2020, 533–534).

use in SM and IT of a highly deficient terminology: "Any attempt to rationalize this deplorable result of a bad terminology must result in obscurity and uneasiness" (Bar-Hillel, 1955, 103). To ameliorate this situation, Bar-Hillel proposed (i) to replace the misleading expression 'Information Theory' popularized in the early-1950s (see Kline, 2015, Chap.3) with another label that won't mislead anyone in believing that Shannon's theory was mainly about the everyday sense of 'information', and fundamentally (ii) to eliminate altogether the use of the term 'information' in the context of IT, and by extension SM. However, he was fully aware that this task of linguistic negotiation should be promoted from within the scientific community and not from outside fields such as philosophy:

> "Even more important than the change of name from Information Theory to Theory of Signal Transmission (…) would be to discard the use of the term 'information' within this theory, with all its ambiguities and semantic traps. It is up to the engineers to revise their terminology, not in order to please some overpedantic philosopher or logician but in order to save themselves futile discussions and to discourage others from ill-advised 'applications'" (Bar-Hillel, 1955, 104)

After Bar-Hillel's proposal of linguistic negotiation in 1955, several authors in the last seventy years have thought that the solution to the conceptual problems underlined in Sect. 4 would necessarily involve a terminological change. Among the most relevant it worth mentioning the one developed by the molecular biologist Jeffrey Wicken in the late-1980s, who proposed replacing the use of the all-pervasive term 'entropy' with the suggestive term 'complexity' in the technical sense of Chaitin and Kolmogorov's algorithmic theory developed in the mid-1960s: "There is, in fact, a completely appropriate alternative to 'entropy' in information theory. This is 'complexity'. What the Shannon formula measures, simply, is complexity of structural relationships." (Wicken 1987, 184). Other novel terms that have been proposed to replace the use of 'entropy' in IT are the portmanteau 'bitropy' (Thims, 2012), or that of 'enformetry' by the statistical mechanical physicist Arieh Ben-Naim (2008), who has also been crusading for several decades to eliminate the notion of 'entropy' not only in IT, but also in SM or even in TD: "I believe that the time is ripe to acknowledge that the term 'entropy', as originally coined by Clausius, is an unfortunate choice. Moreover, it is also a misleading term (…) Perhaps a term like 'enformetry', which has a part from 'entropy', a part the root word of 'information', and 'metry' that indicates a measure of the size of the message, would serve better than 'entropy'." (Ben-Naim, 2008, xv, xix). But, how can a term like 'entropy' (or 'information') be misleading? To answer this question, Wicken pointed out his motivations for making a terminological change:

> "If it were possible to treat 'entropy' simply as an equation, with properties dependent on area of application, calling Shannon's function by that name would be relatively unproblematic. But in point of fact, *most who use the term 'entropy' feel something* of Weaver's conviction about contacting a universal principle which provides sweeping laws of directional change. Precision in the

> use of terms is an important mechanism for keeping our Spencerian ambitions in check. Replacing ‘entropy’ by ‘complexity’ eliminates the connotative field of the second law from arenas of discourse where it does not belong.” (Wicken 1987, 187. Italics added)

What Wicken here calls ‘connotative field’ is explained by what Cappelen (2018, 122–125) refer to as ‘lexical effects’: namely, the set of non-cognitive, non-semantic, and non-pragmatic effects caused by using a linguistic expression. An illustrative example would be what is produced when a child is named ‘Hitler’ simply because his parents phonetically liked that name, but they did not know that there was a someone called Hitler. What Wicken (1987) argues is that by successfully performing a terminological change in the community, the lexical effects caused by using the term ‘entropy’ in the IT sense would then be eliminated, for instance the intuition or feeling that this notion must have some kind of relation with the second law of thermodynamics (as in fact happens with ‘entropy’ in the sense of TD). But according to his proposal, substituting the use of ‘entropy’ for that of ‘complexity’ would simply change the lexical effects caused by the former within the scientific community for those caused by the latter; for example, assuming that ‘complexity’ is a property of systems whose components interact in multiple ways (compatible with ‘entropy’ in the sense of SM, but not in that of TD, since in the latter domain the components are not considered). As for the neologisms ‘bitropy’ or ‘enformetry’, we actually cannot know what kinds of lexical effects they would produce once their use has become established in the scientific community.

In any case, the main shortcoming of the linguistic negotiation strategy is not the substitution of some known disturbing lexical effects for unknown ones, but (1) the assumption that implementing a terminological change is sufficient to solve the various conceptual problems associated to the use of ‘information’ and ‘entropy’; and (2) even assuming that this would be sufficient, its effective implementation in the scientific community would not be possible. First, proponents of linguistic negotiation presuppose that controlling the terms circulating in a community of users implies also controlling the concepts expressed with these terms (Cappelen, 2018, 173–177). However, this is not necessarily the case. Suppose that the use of ‘enformetry’ eventually replaces ‘entropy’, it could still be the case that a significant number of users would continue to use ‘enformetry’ in the IT domain to refer co-extensionally to the same phenomena to which the notions of entropy were applied in TD or SM. In this case, a terminological change would have been made without consequence on how the concepts are used. Second, it would not be possible to effectively change the use of ‘information’ and ‘entropy’ in SM and IT because these linguistic usages are strongly entrenched within the scientific community. After only two decades of entrenchment, this is what Jauch and Baron stated in 1972: “The misleading use of the same name for mathematical and for physical entropy is well-entrenched: *it is now unavoidable*.” (Jauch & Báron 1972, 229. Italics added). And even assuming that we are able to successfully implement linguistic negotiation, we cannot simply make the immense amount of scientific production in SM and IT that depends on these usages, and on which current scientific production depends, simply disappear. In short, we have plenty of reason to believe that the terminological change strategy will not be feasible to ameliorate the conceptual problems associated with the use of 'entropy' and 'information'.

6 Ameliorative Strategy B: Carnap Explicating Entropy and Conceptual Prescriptions

A second plausible strategy would be to prescribe conceptual users the form in which a concept of entropy should be correctly used in order to avoid confusion, such as those associated with the use of 'entropy' and 'information'. Before Bar-Hillel (1955) vindicated a terminological change solution, his teacher Rudolf Carnap was aimed to solve these conceptual problems by means of his conceptual engineering method (or in Machery's [2017, 214] terms 'prescriptive conceptual analysis') called 'Explicatio' (Brun, 2016). The main results of this work carried out around 1952 were published in his posthumous work *Two Essays on Entropy* (Carnap, 1977) edited by Abner Shimony. In it, he attempted to unravel the conceptual underpinnings of the different ways of using 'entropy' and 'information' that were already entrenched among scientists in the early-1950s. To this end, Carnap distinguished between two possible methods for fixing the meaning of the term 'entropy' in SM: (i) Method I, connecting a microscopic descriptions of a molecular system with the values of its measured quantities (volume, temperature, pressure, etc.); or (ii) Method II, connecting microscopic descriptions with some epistemic states of the observer. It is precisely in the latter that the key to these problem lies: "Since the entropy defined by Method II depends upon the specificity of the [microscopic] description it is a logical or epistemological rather than a physical concept. Those statistical mechanicians who conceive of entropy as a measure of lack of information are committed to something like Method II" (Shimony, 1977, ibid., xi).

Once this distinction was draw, Carnap was able to locate one of the focal points of the conceptual confusion that proliferated in the uses of 'entropy' and 'information' of the early-1950s in the use of Method II to provide meaning to this term: "The main result of our discussions is that the general statement of equality of entropy and negative amount of information can be maintained only if Method II is chosen. However, in this case the resulting concept S_B^{II} [epistemic interpretation of Boltzmann entropy] (in any of its versions) is not a physical but a logical concept. *The customary use of the term 'entropy' for this concept is apt to lead to confusion*." (Carnap 1952 [1977], 71–72. Italic added). Thus, according to Carnap, if we assume that by using 'entropy' we are referring to an observer's lack of information about the actual system's microstate, we will not only be implicitly employing Method II, but we are also not using a physical concept (i.e., referring to the system's physical reality) but a proper logical-epistemic notion (i.e., referring to the observer's mental realm). Going one step further, Carnap pointed to Brillouin's popular use of 'entropy' as a measure of the observer's lack of information about the system (see Sect. 3) as a clear-cut example of an epistemic concept of entropy without physical meaning, as we discussed in Sect. 4.1: "In particular L. Brillouin in several articles has investigated the relation between negentropy and amount of information. (…). At any rate, it seems from his discussions that he implicitly uses what we have called

Method II. He does not seem to be aware that the definition of [Boltzmann entropy] which he uses (and which he ascribes to Boltzmann and Planck) makes [S_B] a logical rather that physical concept" (Carnap 1952 [1977], 72–73).

On the basis of this analysis, Carnap (1952 [1977]) sought to solve such conceptual problems by prescribing to scientists that the term 'entropy' should be used in a specific way (i.e., Method I) for it to have a physical meaning, since otherwise (i.e., Method II) this term would express an epistemic notion. The first problem with this strategy lies in the fact that the uses of the term 'entropy' expressing an epistemic notion were not only predominant in the years 1950–1951 as against those expressing a physical notion (see Denbigh, 1981), but also was already deeply rooted in the scientific jargon. This is evidenced in the episode analysed in Anta (2022; also Köhler, 2001) in which Carnap presented in Princeton his prescriptive proposals to scientists such as John von Neumann or Wolfgang Pauli, who not only rejected them but also repudiated them, e.g., "I am quite opposed to the position you [Carnap] take" (Pauli, 1999, 109). After this episode,[15] and after trying for many years to popularize his ameliorative conceptual prescriptions in the scientific community, Carnap was systematically denied publication of his work on the analysis of entropy notions: "I had expected that, in the conversations with the physicists on these problems, we would reach, if not an agreement, then at least a clear mutual understanding. In this, however, we did not succeed, in spite of our serious efforts" (Carnap 1963, 36 quoted on Shimony [2013]). It was precisely one of his disciples, the philosopher Abner Shimony, who, two decades later and after Carnap's death, finally succeeded in editing and publishing *Two Essays on Entropy* (Carnap, 1977).

A second reason why a strategy of conceptual prescriptions such as Carnap's would not be viable is precisely because of the perceived lack of authority of philosophers in SM and IT to prescribe on how scientists should use their own notions. To illustrate this argument, let us come back to Carnap's ameliorative project. In the 1970s and 1980s, Shimony took up Carnap's unfinished task of ameliorating the conceptual problems originated by the entangled uses of 'information' and 'entropy', except in his case focusing on the then-predominantly epistemic usage of 'entropy' promoted by Edwin Jaynes (see Sect. 3). However, Jaynes himself never accepted that Shimony engaged in a critical analysis of the consequences of his proposal: "[Shimony] seems to have made it his lifelong career to misconstrue everything I wrote many years ago, and then compose long pedantic commentaries, full of technical errors and misstatements of documentable facts, showing no awareness of anything done in this field since then -and which, to cep it all off, attack not my statements, but only his own misunderstandings of them." (Jaynes, 1985,135). Ultimately, Jaynes and other scientist working in SM and IT reduced Carnap's and then Shimony's prescriptive conceptual analysis to mere gossip among philosophers: "Of course, if philosophers wish to discuss the rationale of science among themselves,

[15] Bar-Hillel reported this episode: "During one of my visits to him in Princeton, in 1952, von Neumann also came to see him [Carnap], and we started discussing the talk I had heard von Neumann deliver shortly before at an AAAS meeting in St. Louis, in which he had proclaimed, among other things, a triple identity between logic, information theory and thermodynamics (…) We tried to convince von Neumann that this way of presenting the analogy as an identity must lead to confusion"" (Yehoshua Bar-Hillel, quoted on Köhler 2001, 100-101).

in their own journals, without pretending that they are making new contributions to science, they have every right to do so. We physicists also gossip among ourselves about work in other fields" (Jaynes, 1985,134). It is in this harsh claim by Jaynes that one can actually realize that philosophers' generalized lack of authority over the correct use of these concept makes the acceptance of their prescriptions impossible. Because of all these contingent reasons (since it is associated with how the role of philosophical analysis in science was then perceived), a conceptual prescriptive strategy à la Carnap will not be feasible today either as a plausible solution to the deficient use of 'entropy' and 'information' by scientists.

7 Ameliorative Strategy C: Integrating Conceptual Analysis into Scientific Practices

In contrast to the strategy of terminological change, by which conceptual problems can be solved simply by linguistic negotiation, the Carnapian strategy of conceptual prescription did not succeed for contingent reasons: e.g., because the entangled uses of 'entropy' and 'information' and their meanings were already deeply widespread in the scientific community since the early 1950s, and because scientists in SM and IT did not accept the conceptual prescriptions of philosophers as legitimate. In this paper we propose a third conceptual engineering strategy to solve the problem linked to the use of 'entropy' and 'information' in SM and IT. This is based not on (A) proposing to use different terminology, nor on (B) prescribing from philosophical analysis how these terms should be used, but on (C) integrating conceptual analytical prescriptions as a part of the SM and IT-based scientific practices in which the terms 'entropy' and 'information' are used.

But, what do we mean by 'scientific practice'? Here we will minimally rely on Chang's definition of scientific practice as an epistemic activity: i.e., "a coherent set of mental or physical actions (…) that are intended to contribute to the production or improvement of knowledge in a particular way." (Chang, 2011, 209). In this sense, 'integration' must be understood in terms of including a set of relevant mental or physical actions carried out by philosophers of SM and IT (thinking on a term's meaning, mentally assessing how a concept is used, writing about the best form of thinking about a notion, and so on) into the actual domain of actions that can be called statistical mechanical and information theoretical practices. But, this integration cannot be simply done in a stipulative fashion (e.g., unifying the philosophy and the sciences departments) because, as we saw in the case of Carnap, and Shimony (Sect. 6), there has been a generalized perception of philosophers of science as external agents to the scientific practices they analyze. Then, to avoid this obstacle, we propose to integrate conceptual prescriptions as scientific practices by progressively increasing the credentials of conceptual analyses as fruitful philosophical tools in scientific domains.

Our strategy relies on what Pradeu et al., (2024) have recently labeled as 'Philosophy *in* Science' (closely inspired on Chang's [2004, Ch.6] 'complementary science'), a methodology by which philosophers of science can effectively contribute to science by using their philosophical tools. In our case, we specifically claim that the history and philosophy of SM and IT can contribute to solving (or at least mitigating) the manifold of problems associated to the entropy-information entanglement by integrating their descriptive, evaluative and also prescriptive (i.e., engineering) conceptual analyses as part of the scientific practices in which such problems arise. The main idea is that we might progressively increase the credentials of conceptual analysis and prescriptions as philosophical tools that can contribute to obtain knowledge in scientific practices by providing a lot of robust evidence of this contribution being actually the case. Where can we find this evidence? In their work, Pradeu et al., (2024, 406) assessed a vast amount of bibliographic data to support the idea that there have been several philosophers of science that have actually contributed to science by using philosophical tools. They identified at least 136 high-impact works in this sense. Particularly, they collected evidence in favor of the actual contribution generated by the conceptual analysis (as a tool) of the notions 'death' by Bernat et al. (1981) in biomedicine, 'reproduction' by Godfrey-Smith (2015) in evolutionary biology, or 'complex system' by Ladyman et al. (2013) in various fields. Furthermore, they evaluated the interesting case of Shimony's (1995) conceptual analysis of the concept of 'quantum mechanical entanglement' as clearly contributing to develop new methods to quantify the degree of entanglement in the late-1990s (Pradeu et al., 2024, 405).

Additionally, we rely on Pradeu et al.'s method to argue that conceptual analyses of 'entropy', paradigmatically the one developed by Roman Frigg and Charlotte Werndl (2011) in 'Entropy—A Guide for the Perplexed', have also constituted a case of 'Philosophy *in* Science' (in Pradeu et al. terms) which has somehow contributed to disentangle conceptual misuses among scientists. A Google Schoolar citation analysis reveal that only 28.2% of this paper's 130 citations come from philosophy, the rest (71.8%) come from some STEM field in which the concepts of entropy and information are frequently used: 41.0% theoretical physics and applied math, 23.06% engineering and biomedicine, and 7.69% others.[16] Although this citation data only means that Frigg-Werndl analysis had a enormous penetration ('intervention' in Pradeu et al., (2024) terms) in the STEM community, by performing a qualitative assessment of the 90 STEM texts one could conclude that at least 37 explicitly recognized its contribution, either by prescribing a conceptual distinction, e.g., "As noted by Frigg and Werndl (2011), there is an important difference between the discrete and continuous Shannon entropy" (Petty, 2018, 1012) or a conceptual connection, e.g., "Equation [Boltzmann entropy] can be derived from course-graining a classical phase space, as shown by Frigg and Werndl (…)" (Davidson, 2018). This can be seen as supporting the idea that the analyses of entropy concepts like Frigg and Werndl's (2011) (also Uffink's [2007]; Shenker's [2020], etc.) have been at some extent integrated as scientific SM practices in Chang's (2011) sense, since these philosophical epistemic activities are actually affecting how SM physicists are drawing conceptual distinctions and connections, and, as a consequence (see Sect. 4), also contributing to improve these conceptual practices in SM. Thus, it

[16] This figures were obtained by performing a citation analysis [date May 15.th 2024] on the following data: https://scholar.google.es/scholar?oi=bibs&hl=es&cites=14461528832453857486,11185336550053508262

could be prima facie plausible to progressively increase the credentials of 'philosophers *in* SM' (qua analysers of entropy concepts) among target users by popularizing the evidence of their contribution, therefore increasing in a virtuous circular fashion the assimilation of conceptual analyses and prescriptions as constitutive part of SM's practices.

Apart from the usual science communication channels, a solid way to popularize in the long run the evidentially supported contribution of philosophical tools in science is by pedagogical means. An interesting proposal in the one suggested by Matthews (1994, 2015), who developed a curricula strategy to include in science programs advanced training in HPS focused on promoting the virtues of conceptual analysis (among other philosophical tools) as scientific practices. For instance, he showed that analyzing the concept of 'pendular motion' might be theoretically and experimentally fruitful to obtain scientific knowledge about pendular phenomena (Matthews, 1994, 109–135). In our particular case, these pedagogical-curricular strategies à la Matthew can be exploited to teach (relying on the set of evidence reported above) the next generations of scientists the fruitfulness of including conceptual analyses of 'entropy' and 'information' as scientific practices in SM or IT, therefore boosting the credentials of philosophers as conceptual prescribers in these fields. It should be clarified that our proposal is not based on defending philosophy *in* SM (in Pradeu et al., (2024) terms) as an already adopted method, but moreover to use the evidence of how this trend has actually contributed to this domain to foster a closer integrative collaboration between SM specialists and philosophers of SM that will progressively lead to ameliorate the defective uses of 'entropy' and 'information' by scientists following a set of conceptual prescriptions.

As we argued in Sects. 6 and 7, the terminological prescriptions of Bar-Hillel, or the conceptual ones of Carnap or Shimony had no effect on the scientific community of 1950–1980 due to several factors, among them the low credentials of philosophers as prescribers. Unlike strategy A and B, the conceptual engineering strategy C is not focused on specific solutions, but on progressively implementing the manifold of socio-epistemic conditions that would have led scientists to accept Carnap or Shimony's conceptual prescriptions in the 1950s and 1980s, respectively, as many have recently learned from conceptual analyses such as Frigg and Werndl's in the 2010s. In other words, strategy C is aimed at what is called in the conceptual engineering literature the 'implementation challenge' (Isaac et al., 2022). The main reason to not fucus on domain-general solutions is because all the problems derived from entropy-information entanglement are so entangled in the scientific practices that there cannot be a single effective solution for all of them. For example, prescribing a sharp conceptual distinction between entropy notions can work for theoretical physicists, but not for computer engineers; or prescribing to use a highly restricted concept of information might work for some early-career researchers but not for consolidated scientists, and so on.

Thus, because of this lack of domain-general solutions, we should choose an amelioration strategy like C, based on strongly promoting a systematic, immediate, and close coordination between (i) philosophers *in* science as conceptual prescribers and (ii) special scientists as conceptual users, then connecting their epistemic activities and outputs (mainly, domain-restricted ameliorative solutions to local conceptual problems) via what Galison (1997, Ch.9) called ‘trading zones’.[17] Interestingly, this fruitful kind of epistemic trading can now become effectively implemented because, unlike Bar-Hillel, Carnap or Shimony in the 1950-1980s, contemporary philosophers *in* science have now at their disposal an enormously valuable currency to exchange their conceptual amelioration proposals into the trading zones: namely, the evidence that these philosophical tools can effectively contribute to improve defective conceptual practices in scientific fields.

8 Conclusion

The convoluted use of terms like ‘entropy’ and ‘information’, which became widespread in the 1950s, has resulted in various conceptual deficiencies. Recognizing this issue, several philosophers have pursued different strategies to address it under the banner of ‘conceptual engineering’. One of the most common approaches, initiated by Bar-Hillel in 1955, has been to recommend changing the terminology to reduce confusion. Others, like Carnap (circa. 1951–1952) and Shimony (in the 1970s-1980s), proposed normative guidelines on how these terms should be used in order to make them more meaningful. Finally, in this paper we have articulated a third strategy, which does not aim to replace the earlier efforts but rather complement them. As such, our strategy to ameliorate those conceptual practices involving ‘entropy’ and ‘information’ seeks not only to revive the work of Bar-Hillel, Carnap, and Shimony, but moreover it seeks to capitalize on recent analyses of these concepts (e.g., Uffink, 2007; Frigg & Werndl, 2011; Shenker, 2020) as amelioration tools. But, unlike previous attempts, the prospects of actually mitigating this conceptual confusion are based on warranting that some ameliorative proposals can be effectively implemented in the scientific community. And to successfully do so, our conceptual engineering strategy rests on leveraging Philosophy-in-Science evidence (see Pradeu et al., 2024) to convince the scientific community of users that accepting conceptual prescriptions from philosophers of science can lead to a significant improvement in their conceptual practices. It is precisely in this sense that the ‘complementary’ (in words of Chang’s [2004]) contribution of the philosophical analysis of concepts like entropy and information might be central in enhancing the quality of our best scientific knowledge.

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[17] Although Galison (1997, Ch.9) originally developed the concept of ‘trading zones’ to refer to different epistemic traditions in science, it could be also used to refer to non-scientific traditions like philosophical ones.

Declarations

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Ethical Approval I hereby confirm that this research follows all the ethical standards of Erkenntnis.

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