From Arithmetic to Metaphysics

A Path through Philosophical Logic

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Exploring and extending the landscape of conjunctive approaches to verisimilitude

Abstract: Starting with Popper, philosophers and logicians have proposed different accounts of verisimilitude or truthlikeness. One way of classifying such accounts is to distinguish between "conjunctive" and "disjunctive" ones. In this paper, we focus on our own "basic feature" approach to verisimilitude, which naturally belongs to the conjunctive family. We start by surveying the landscape of conjunctive accounts; then, we introduce two new measures of verisimilitude and discuss their properties; finally, we conclude by hinting at some surprising relations between our conjunctive approach and a disjunctive account of verisimilitude widely discussed in the literature.

We thank Theo Kuipers and Luca Tambolo for reading a first draft of this paper and providing useful feedback. The first author gladly recalls how he was strongly inspired by Sergio's concept of an "enlarged reason", according to which the sophisticated tools of modern logic, traditionally applied in the philosophy of mathematics and of science, can be fruitfully employed also in other areas, including epistemology, ontology, and rational theology. In particular, the present authors are both inclined to believe that the logical notions of probability and verisimilitude will reveal very useful in these areas of philosophical research. In support of this, the two quotations opening this paper intend to suggest that the concern for verisimilitude, or truth approximation, is shared within a wide spectrum of philosophical tendencies, from Christian theology to Marxism. A fascinating historical account of the origins of the concept of verisimilitude and the related development of realist and fallibilist views of knowledge – from Carneades and St. Augustine to Cusanus and Peirce, from Engels and Lenin to Popper – is given by Niiniluoto (1987, ch. 5).

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> Human conceptions [. . .] are relative, but these relative conceptions go to compound absolute truth. These relative conceptions, in their development, move towards absolute truth and approach nearer and nearer to it.
>
> V. I. U. Lenin, *Materialism and Empirio-Criticism*, 1908

> [S]cience and theology [. . .] share a common conviction that there is truth to be sought. Although in both kinds of enquiry this truth will never be grasped totally and exhaustively, it can be approximated to in an intellectually satisfying manner that deserves the adjective 'verisimilitudinous', even if it does not qualify to be described in an absolute sense as 'complete'.
>
> John Polkinghorne, *Quantum Physics and Theology*, 2007

1 Introduction

Explicating verisimilitude has proved a challenging task since Popper first introduced the notion in 1963. After Popper's definition was shown to be untenable (Miller (1974), Tichy (1974)), logicians and philosophers of science have put forward a number of competing explications of what does it mean for a theory or hypothesis h to be closer to the truth than another one (for surveys, see Niiniluoto (1998) and Oddie (2014)). As a result, the conceptual landscape of different accounts of verisimilitude is now quite crowded. In the attempt to put some order in this landscape, verisimilitude theorists have recently devised alternative classifications of existing accounts of this notion (Zwart (2001); Zwart and Franssen (2007); Schurz and Weingartner (2010); Schurz (2011); Oddie (2013, 2014)). In this paper, we aim at exploring and extending what Schurz (2011) calls the "conjunctive" approach to verisimilitude (as opposed to the "disjunctive" one).

We proceed as follows. In section 2, we briefly survey the post-Popperian research program on verisimilitude and draw a pocket map of the landscape of conjunctive accounts of verisimilitude. Then, in Section 3 we focus on the "basic feature" approach to verisimilitude, which has been developed in some recent papers by the present authors[1]. We present two new measures of verisimilitude

1 For early versions and motivations, see Festa (2007a,b,c, 2009, 2011, 2012) and Cevolani et al. (2011) for a more detailed exposition; for discussion of some applications see Cevolani (2011, 2013, 2014a,b, 2015, 2016), Cevolani and Calandra (2010), Cevolani and Crupi (2015), Cevolani and Festa (2009), Cevolani et al. (2010, 2011, 2012)), and Cevolani et al. (2013). Note that Theo Kuipers' explication of "descriptive verisimilitude" (Kuipers, 1982) anticipates some of the key ideas of the basic feature approach.

grounded on our basic feature approach, the second being a generalization of the first, which in turn is a generalization of the original measure presented in our previous contributions. In Section 4, we conclude by hinting at some surprising relations between our measures and other well-known verisimilitude measures.

2 Conjunctive approaches to verisimilitude

We start by introducing a small amount of notation and terminology in section 2.1. In section 2.2, we present Popper's original definition of verisimilitude and the post-Popperian research program arising from its failure. We then focus on so called conjunctive approaches to truthlikeness in section 2.3.

2.1 A propositional framework for verisimilitude

We assume that "the world" is described by a propositional language L_n with n atomic propositions $a_1, \ldots, a_n$.[2] Within L_n, one can express 2^{2^n} logically distinct propositions, including the tautological and the contradictory ones; as usual, these are denoted $\top$ and $\perp$, respectively. Given two propositions h and g, h is said to be logically stronger than g when h entails g but g does not entail h (in symbols: $h \vDash g$ but $g \nvDash h$). Figure 1 displays the $2^{2^n} = 16$ propositions of L_2–with p and q as atoms. We shall make use of this toy language to illustrate some features of the definitions of verisimilitude discussed in the paper, and to compare them.

Among the factual, i.e., neither tautological nor contradictory, propositions of L_n, some play a special role and deserve special mention. A basic proposition is an atom or its negation (e.g., p, $\neg p$, q, $\neg q$ are the basic propositions of L_2 in Figure 1). The notation $\pm a_i$, where "$\pm$" can be "$\neg$" or nothing, will be employed to denote an arbitrary basic proposition of L_n.

A conjunction $\pm a_1 \wedge \ldots \wedge \pm a_m$ of m basic propositions ($0 \leq m \leq n$), at most one for each atomic one, will be called a *conjunctive proposition* of L_n. If $m = 0$, then the conjunctive proposition is tautological; if $m = 1$, it is a basic proposition; and if $m = n$, it is a so called *constituent* of L_n. Note that the $q = 2^n$ constituents $z_1, \ldots, z_q$ are

2 One may argue that an adequate explication of verisimilitude should not be restricted to theories stated in simple propositional languages. Still, as shown for instance in the works quoted in the previous note, verisimilitude measures for propositional theories prove both adequate and fruitful in the analysis of some relevant issues in formal epistemology and the philosophy of science

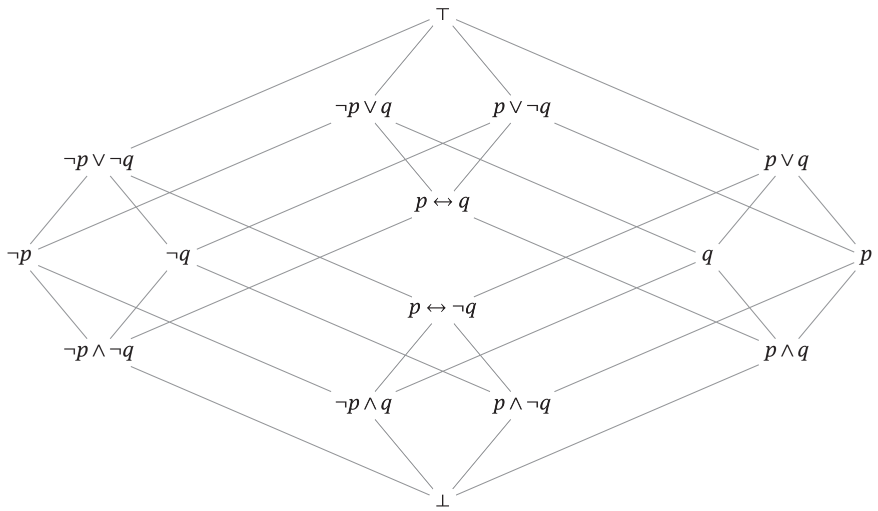

Fig. 1. The 16 (logically distinct) propositions of language L_2 (with atoms p and q) represented in increasing order of logical strength, from the top to the bottom of the diagram: if two propositions are (directly or indirectly) connected, the upper one is a consequence of the lower one.

the logically strongest factual propositions of L_n. As Figure 1 shows, constituents are weaker than a contradiction but stronger than any other proposition (the constituents of L_2 are the four conjunctions $p \wedge q$, $p \wedge \neg q$, $\neg p \wedge q$, and $\neg p \wedge \neg q$). The negation of a constituent, i.e., a disjunction of the form $\pm a_1 \vee \ldots \vee \pm a_n$, is called by Carnap (1950b, p. 405) a content element of L_n (in Figure 1, $p \vee q$, $p \vee \neg q$, $\neg p \vee q$, and $\neg p \vee \neg q$ are the four content elements of L_2). These are the weakest factual propositions of L_n, stronger than a tautology but weaker than any other proposition.

Note that each constituent is logically incompatible with any other, and that only one of them can be true; the true constituent is denoted t and is the strongest true proposition expressible in L_n. Intuitively, a constituent completely describes a possible world, i.e., a possible state of affairs of the relevant domain; thus, t can be construed as "the (whole) truth", i.e., as the complete true description of the actual world in $\mathcal{L}_n$. When one of the constituents of L_n is identified with the truth t, it partitions the set of propositions of L_n into the class $T = Cn(t)$ of the true ones and its complement F, containing the false ones. In the following, we shall assume, for the sake of illustration, that $p \wedge q$ is the truth of the toy language in Figure 1.

The *specular* of a conjunctive proposition $\pm a_1 \wedge \ldots \wedge \pm a_m$ is the conjunction of the negations of all its basic propositions $\pm a_i$.[3] As an example, in Figure 1 $\neg p \wedge \neg q$ is the specular of the truth $p \wedge q$. In general, the specular of the truth is denoted f. Intuitively, f can be construed as the "worst" constituent of L_n, i.e., as the completely false description of the actual world. Note the difference between the specular of the truth f – i.e., $\neg p \wedge \neg q$ in Figure 1 – and the negation of the truth $\neg t$, which is the only false content element of L_n – i.e., $\neg p \vee \neg q$.

Any proposition h of L_n is construed here as expressing a possible theory or hypothesis about the world. Intuitively, the verisimilitude of h depends on how much true information h provides about the world. In this connection, let $Cn(h) = \{g : h \vDash g\}$ be the class of propositions entailed by h (where Cn denotes the operation of classical logical consequence), i.e., what Popper (1963b, p. 218) called the "logical content" of h. For our purpose, it will be useful to consider also the "basic content" of h, i.e., the set $B(h) = \{\pm a_i : h \vDash \pm a_i\}$ of the basic propositions entailed by h or, as we may say, of the basic consequences of h. Of course, for any $h, B(h) \subset Cn(h)$, i.e., all basic consequences of h are consequences of h.

Finally, few words about probability. A probability measure m defined on the propositions of L_n is called a *logical* probability measure when it assigns to each constituent z_i of L_n the same value $m(z_i) = 1/2^n$ (cf. Carnap 1950b, ch. 5). For any proposition h of L_n, $m(h)$ is the proportion of constituents entailing h out of the total number of constituents:

(1) $$m(h) = \sum_{z_i \vDash h} m(z_i) = \frac{|\{z_i : z_i \vDash h\}|}{2^n}$$

It follows that all basic propositions have the same degree of logical probability:

(2) $$m(\pm a_i) = 1/2$$

3 This notion of specularity was first introduced, as far as we know, by Festa in an unpublished 1982 manuscript; a summary of his results was then provided by Niiniluoto (1987, p. 319–321). Roughly in the same years, Oddie (1986, pp. 49–50) introduced the term "reversal" to denote the same concept (defined for arbitrary propositions, not just conjunctive ones). The term "inverse" has then been used later by Zwart (2001, p. 25) to refer to the same notion. In this connection, one should note that Zwart (*ibidem*, pp. 32 ff. and 56 ff.) discusses also a "specularity property" and acknowledges, following Kuipers (1987b, p. 85), that "the term is Roberto Festa's" (*ibidem*, note 66); however, he doesn't mention that, despite the common terminology, Festa's notion of "specular" and Kuipers' specularity property are actually quite unrelated (cf. Festa (1987, p. 153 ff)).

Assuming that h is consistent (as we shall always assume in the following), the conditional logical probability of g given h is defined as usual, i.e., $m(g|h) = m(h \wedge g)/m(h)$. This is the proportion of the cases (i.e., constituents) in which g is true out of the total number of cases in which h is true. If $m(g|h) > m(g)$, i.e., if h raises the initial proportion of cases in which g is true, it is customary to say that h is positively *relevant* for g.[4] Following Salmon (1969, p. 63), if h is positively relevant for g we shall say that h partially entails g or, equivalently, that g is a partial consequence of h. Note that, if h (fully) entails g, then g is true in all cases where h is true; in other words, any non-tautological consequence of h is also a partial consequence of h.

It also follows immediately that, as far as basic propositions are concerned, h partially entails $\pm a_i$ just in case $m(\pm a_i|h) > 1/2$. Accordingly, we call $b(h) = \{\pm a_i : m(\pm a_i|h) > 2\}$ the set of partial basic consequences of h. To illustrate, one can check, with reference to Figure 1, that the partial basic consequences of, say, $p \vee \neg q$ form the set $b(p \vee \neg q) = \{p, \neg q\}$. Of course, any basic consequence of h – i.e., any basic proposition “fully” entailed by h – is also a partial basic consequence of h: in other words, we have that $B(h) \subset b(h)$.

2.2 The post-Popperian research program on verisimilitude

In the early sixties of the past century, the controversy between Popper’s and Carnap’s followers concerning the goals of science and the growth of knowledge urged Popper (1963b, ch. 10) to introduce the first formal explication of verisimilitude. Popper believed that science aims neither at highly probable nor at inductively well confirmed theories, but at theories with a high degree of verisimilitude, a notion which “represents the idea of approaching comprehensive truth [and] thus combines truth and content” as the two fundamental cognitive goals of inquiry (Popper, 1963b, p. 237).

In Popper’s intentions, the idea of verisimilitude should have supported his realist and falsificationist views about science, by showing how it is possible to keep together two apparently opposite tenets: i.e., that our best theories are bold conjectures which are likely false (and will be quite surely falsified in the future) and that still science progresses toward truth. If a false theory can be closer to the truth than another false theory, Popper argued, then one can coherently maintain

4 For a detailed analysis of the concepts of positive and negative relevance see Carnap (1950a, cg. 6) and Salmon (1969).

a falsificationist attitude in methodology and a realist view of the main aim of science, i.e., truth approximation.[5]

In order to defend the ideas outlined above, Popper (1963b) introduced a definition of verisimilitude based on an apparently very sound intuition: the more true propositions and the less false propositions a theory h entails, the greater its verisimilitude. More precisely, recalling that $Cn(h)$ is the class of consequences of h, let $Cn_T(h) = Cn(h) \cap T = Cn(h) \cap Cn(t)$ denote the class of true consequences of h, and $Cn_F(h) = Cn(h) \cap F$ the class of false consequences of h, to the effect that $Cn_T(h) \cup Cn_F(h) = Cn(h)$. Then, according to Popper (1963b, p. 233), h is closer to the truth than g if and only if h has no less true consequences than g (and possibly more) and no more false consequences (and possibly less).

Definition 1 (Popperian verisimilitude). *h is at least as close to the truth as g iff:*

$$Cn_T(h) \supseteq Cn_T(g) \text{ and } Cn_F(h) \subseteq Cn_F(g)$$

Moreover, h is closer to the truth than g if at least one of the above inclusion relations is strict.

When Definition 1 first appeared in the tenth chapter of *Conjectures and Refutations*, it didn't attract much attention, perhaps because most readers found the definition exactly as it should be (cf. Kuipers 2000, p. 139). Popper's definition became famous about ten years later, when Miller (1974) and Tichý (1974) independently proved that it was completely inadequate. More precisely, they showed that no false theory h can be closer to the truth than another (true or false) theory g according to Popper's Definition 1. This so called Tichý-Miller theorem proved fatal for Popper's explication of verisimilitude, since it showed that Definition 1 is worthless for the very purpose for which Popper introduced it – i.e., ordering false theories according to their closeness to the truth.

The surprising failure of Popper's attempt urged logicians and philosophers of science to develop more adequate definitions of verisimilitude. As a result, the conceptual landscape of different accounts of verisimilitude is now very crowded, different scholars having put forward a number of competing and partially conflicting explications of what does it mean for a theory to be closer to the truth than another one (for an early collection, see Kuipers (1987a) and, for surveys, see Niiniluoto (1998) and Oddie (2014)). At the moment, the work in

5 For most recent critical discussion about this view of scientific progress, see, e.g., Cevolani and Tambolo (2013a), Niiniluoto (2014) and Rowbottom (2015).

this area follows three different paths. First, the search for adequate explications of verisimilitude is still an active area of study, as the contributions by, e.g., Festa (2007a,b,c), Schurz and Weingartner (2010), Cevolani et al. (2011), Northcott (2013), and Kuipers (2015) testify. Second, such explications are being applied to the analysis of both classical problems in the philosophy of science (see, e.g., Cevolani and Tambolo (2013a,b), Cevolani et al. (2013), Tambolo (2015), Niiniluoto (2014, 2015) on the analysis of scientific progress) and of issues in formal epistemology or even cognitive psychology (see, e.g., Cevolani et al. (2010, 2012); Cevolani and Crupi (2015); Cevolani and Schurz (2017) on the analysis of paradoxes of rational belief, and Cevolani and Calandra (2010), Cevolani et al. (2011), Kuipers (2011), [Niiniluoto 2011], and Schurz (2011) on the connections between verisimilitude and belief revision). Finally, verisimilitude theorists have recently devised alternative classifications of existing accounts of this notion, in order to investigate the differences, similarities, and possible connections among the different approaches (Zwart (2001); Zwart and Franssen (2007); Schurz and Weingartner (2010); Schurz (2011); Oddie (2013, 2014)). Our point of departure is this recent debate on the most appropriate way to classify accounts of verisimilitude, and in particular the distinction between "conjunctive" and "disjunctive" approaches, to which we now turn.

2.3 Mapping the landscape of conjunctive accounts of verisimilitude

In some recent papers, Gerhard Schurz has convincingly argued that the way in which theories are represented in the first place can have significant implications in assessing their verisimilitude (Schurz and Weingartner (2010), Schurz (2011)). More precisely, he distinguishes two approaches to theory representation. Within the first, a theory h is represented as a conjunction of minimal "content parts", i.e., of the smallest items of information provided by h on the world; as an example, h may be the conjunction of its consequences in some language. The second approach instead represents h as a disjunction of maximal "alternative possibilities", like the possible worlds or the models of the underlying language. Of course, the above distinction parallels the familiar one between two equivalent ways of expressing sentences in formal languages, namely, the one between conjunctive and disjunctive normal forms.[6]

6 As immaterial as this distinction may be from a purely logical point of view, it can have significant implications for the formal analysis of epistemological concepts, including verisimilitude, as Schurz and Weingartner (2010, p. 424) observe (cf. also Carnap (1950a, §72–73), especially p. 407).

Within both approaches, one can distinguish different accounts of verisimilitude, according to the different ways of construing the relevant notion of either content part or alternative possibility. Here, we shall focus only on the conjunctive approach. Schurz (2011, csec. 2.2) surveys five conjunctive accounts of verisimilitude proposed in the literature, including our own basic feature approach, to be discussed in greater detail in Section 3. All these accounts retain the following fundamental Popperian intuition:

> *h* is at least as close to the truth as *g* iff
> all true content parts of *g* are also true content parts of *h* and
> all false content parts of *h* are also false content parts of *g*.

However, they differ on how these content parts are defined. The following list displays, in order of appearance in the literature, a number of conjunctive accounts, including the ones identified by Schurz (2011).

- In Popper's account (cf. Definition 1), the content parts of *h* are arbitrary logical consequences of *h*; as mentioned, such an account is untenable due to the Tichý-Miller theorem. All other accounts mentioned below eschew his problem.
- In Mortensen's (1978; 1983) account, classical logic is abandoned in favour of a relevant logic, to the effect that not all classical consequences of *h* count as relevant consequences of *h*.
- In the "short theorems" account (Mott, 1978), the content parts of *h* are special consequences of *h*, comparable to, but different from, the relevant consequences in Schurz's and Gemes' accounts below.
- In the "relevant element" account (Schurz and Weingartner, 1987, 2010; Schurz, 2011), the content parts of *h* are relevant consequences of *h*, according to the definition of relevance developed by Schurz in a number of papers (see especially Schurz 1991).
- In Gemes (2007)' account, the content parts of *h* are also relevant consequences of *h*, but the notion of relevance is different from the one employed by Schurz.
- In the "basic feature" account (e.g., Cevolani et al. 2011), the content parts of *h* are the "basic" consequences of *h*, i.e., the basic propositions entailed by *h*.
- In the "Carnapian" account (Cevolani 2016), the content parts of *h* are the content elements (in the sense of Carnap 1950b, p. 405) entailed by *h*, i.e., its weakest factual consequences.

With the exception of Popper's one, all the above accounts have a trait in common: the set of content parts of *h* is a proper subset of the class of its logical consequences (cf. Schurz 2011, p. 206). This means that only some of the consequences of h are deemed relevant as far as verisimilitude assessments are concerned. In all cases, this is sufficient to avoid the unwelcome consequences of the Tichý-Miller theorem. Moreover, all conjunctive accounts (including Popper's one) meet what Oddie (2013, p. 1651) calls the "strong value of content for truths" principle, i.e, the requirement that, among truths, verisimilitude increases with content:

> if h and g are true and h is logically stronger than g,
> then h is more verisimilar than g.

This principle – or at least its weaker version, saying that if h is true and entails g, then h is at least as close to the truth as g – is regarded by most verisimilitude theorists, including Popper himself, as "an essential desideratum for any theory of verisimilitude" (Oddie, 2014, sec. 1). For these and other reasons, Schurz and Weingartner (2010, sec. 3) defend conjunctive accounts as intrinsically plausible and delivering cognitively more manageable assessments of verisimilitude.

Interestingly, the landscape of conjunctive approaches seems to be conceptually delimited by two extreme positions. The first is represented by Popper's original definition; the second is the newly introduced "Carnapian" definition of verisimilitude (see Cevolani 2016, for details). While for Popper verisimilitude depends on the set of all the consequences of h, assessments of Carnapian truthlikeness are based only on the set of the weakest consequences of h, i.e., the content elements entailed by h. Between these two extremes, one can arguably place all other conjunctive accounts, according to the different classes of consequences of h they isolate as relevant for verisimilitude comparison. Notably, both the extremes are inadequate as accounts of verisimilitude, but for different reasons: the Popperian account because of the Tichý-Miller theorem, and the Carnapian account since it meets the implausible condition according to which verisimilitude increases with logical strength (not only among true but also) among false theories:

> if h and g are false and h is logically stronger than g,
> then h is more verisimilar than g.

Such condition, that Oddie (2013, p. 1654) has dubbed "the strong value of content for falsehoods", is rejected by virtually all verisimilitude theorists, the only exception being David Miller, whose favoured account of verisimilitude satisfies it (cf. Miller 1978, 1994, 2006).

3 The basic feature approach to verisimilitude

In this section, we focus on our own conjunctive account of verisimilitude of propositional theories, i.e., the basic feature approach. We proceed in two steps, presenting in turns two variants of this approach. In the first, the verisimilitude of h depends on the *categorical* information that h provides about the basic features of the world (section 3.1). A discussion of the limitations of this version then leads to a second, refined one, according to which the verisimilitude of h is measured in terms of the partial information provided by h about the basic features of the world (section 3.2).

3.1 Verisimilitude as categorical information about the basic features of the world

The key intuition underlying most explications of verisimilitude can be expressed as follows: a theory h is verisimilar when h tells many things about the world and many of these things are true. In this sense, as Popper (1963b, p. 237) noted, the idea of verisimilitude "combines truth and content": h has to provide much information about the world, and most of this information has to be true, in order to make h (highly) verisimilar. Within the basic feature approach, the verisimilitude of h only depends on what h says about the basic features of the world. These are n independent facts which may or may not obtain in the world (like "it's raining" and "it's not raining") and are described by the atomic propositions of L_n. Accordingly, the key intuition above can be rephrased as follows: h is verisimilar when h provides much information about the basic features of the world and most of this information is true (cf. Cevolani et al. 2011).[7]

An immediate refinement of the above intuition concerns quantitative verisimilitude, i.e., the definition of an appropriate measure of the verisimilitude of a theory h. We will assume that such measure depends only on the *amount* of true and false information that h provides about the basic features of the world. More precisely, we require that the verisimilitude of h is an increasing function of the amount of true information and a decreasing function of the amount of false information provided by h on those basic features. There are many different ways

7 If rather sparse, consonant intuitions are recurrent in the literature on verisimilitude; cf., e.g., Brink and Heidema (1987, sec. 4); Oddie (1987, sec. 2), Kuipers (1982). Interestingly, similar ideas also appear in the field of "veristic social epistemology" (cf. Goldman (1999, sect. 3.4).

of specifying such a function; two of them will be discussed in this and the next section.

Recalling that $B(h) = \{\pm a_i : h \vDash \pm a_i\}$ is the set of the basic consequences of h, its cardinality $|B(h)|$ arguably provides a simple measure of the total amount of information provided by h about the n basic features of the world. In fact, this is equivalent to saying that (i) the amount of information provided by h about $\pm a_i$ is 1 if h entails either a_i or its negation $\neg a_i$, and is 0 in the case where h entails neither of them; and, (ii) the total amount of information provided by h about the n basic features of the world is just the sum of the amount of information provided by h about each of them. By dividing this number of basic consequences of h by n, the following normalized measure is obtained:

(3) $$Inf(h) \equiv \frac{|B(h)|}{n}$$

As one can check, $Inf(h)$ varies between the minimum information provided by a tautology and the maximum information provided by a constituent:

(4) $$Inf(\top) = 0 \leq Inf(h) \leq 1 = Inf(z_i)$$

Using now Popper's definitions (presented in Section 2.2) as a benchmark, we shall say that $B_T(h) = B(h) \cap T$ is the class of true basic consequences (or of basic truths) of h, and $B_F(h) = B(h) \cap F$ the class of its false basic consequences (or basic falsehoods). Accordingly, the amount $Inf_T(h)$ of true information provided by h about the n basic features of the world may be defined along the same lines of definition (3):

(5) $$Inf_T(h) \equiv \frac{|B_T(h)|}{n}$$

In the same way, the amount $Inf_F(h)$ of false information provided by h about the n basic features of the world is defined as:

(6) $$Inf_F(h) \equiv \frac{|B_F(h)|}{n}$$

It is easy to check that the information $Inf(h)$ provided by h is the sum of the true and false information provided by h:

(7) $$Inf(h) = Inf_T(h) + Inf_F(h)$$

Interestingly, a simple measure of the verisimilitude of h is obtained from (7) by replacing the "plus" sign with the "minus" one:

(8) $$Vs(h) \equiv Inf_T(h) - Inf_F(h)$$

In words, the verisimilitude of h is the difference between the amount of true and false information provided by h about the basic features of the world.[8]

The following inequalities are immediate consequences of definition (8):

$$Vs(f) = -1 \leq Vs(h) \leq 1 = Vs(t) \tag{9}$$

$$Vs(\top) = 0 \tag{10}$$

Note that (9) says that $Vs(h)$ varies between -1, i.e., the verisimilitude of the complete falsehood, and 1, i.e., the verisimilitude of the truth. Equality (10) shows that the verisimilitude of a tautology is a sort of natural middle point: $Vs(h) > 0$ iff the number of basic truths exceeds the number of basic falsehoods of h, while $Vs(h) < 0$ iff the number of basic falsehoods exceeds the number of basic truths of h.

The definition of verisimilitude just presented is essentially identical to the one proposed in our earlier work as limited to the class of conjunctive theories. For this kind of theories, as we argued in those earlier contributions, *Vs* provides perfectly adequate assessments of verisimilitude. Here, definition (8) is given for arbitrary theories, so that *Vs* is intended to measure the verisimilitude of both conjunctive and non-conjunctive ones. However, it is easy to show that, as a general measure of the verisimilitude for propositional theories, *Vs* is inadequate.

To see this, let us define the "conjunctive counterpart" of h, denoted $c(h)$, as the strongest conjunctive statement entailed by h or, equivalently, as the conjunction of the basic propositions entailed by h. It is now easy to check that, according to *Vs*, the verisimilitude of h is equal to the verisimilitude of its conjunctive counterpart:

$$Vs(h) = Vs(c(h))$$

This already raises a problem for *Vs*. In fact, it is clear that two theories h and g may have the same conjunctive counterpart even if they are not logically equivalent. As an example, one can check that any possible disjunction of basic propositions has the same, tautological counterpart:

$$c(\pm a_1 \vee \pm a_2) = c(\pm a_1 \vee \pm a_2 \vee \pm a_3) = c(\pm a_1 \vee \pm a_2 \vee \ldots \vee \pm a_n) = c(\top) = \top.$$

This fact is sufficient to show that *Vs* is a very coarse grained measure, since it assigns the same degree of verisimilitude to significantly different theories. In

8 As an immediate consequence of equalities (7) and (8), we find that $Vs(h)$ can be expressed in terms of $Inf(h)$ and $Inf_F(h)$ or, alternatively, in terms of $Inf(h)$ and $Inf_T(h)$: $Vs(h) = Inf(h) - 2Inf_F = 2Inf_T - Inf(h)$.

particular, if h is non-tautological but so weak that it doesn't entail any basic proposition, then h is assigned the same verisimilitude as the tautology, namely 0. For instance, whatever the truth t of L_n, one obtains that:

$$Vs(\pm a_1 \vee \pm a_2) = Vs(\pm a_1 \vee \pm a_2 \vee \pm a_3) = Vs(\pm a_1 \vee \pm a_2 \vee \ldots \vee \pm a_n) = Vs(\top) = 0.$$

As another example, with reference to Figure 1, all the content elements of L_2, as well as $p \leftrightarrow q$ and $p \leftrightarrow \neg q$, are deemed as truthlike as a tautology.

The equalities above show that *Vs* doesn't deliver intuitively sound verisimilitude assessments for non-conjunctive theories. Fortunately, as we argue in detail in section 3.2 below, there is a natural way of defining a verisimilitude measure for arbitrary theories which improves on *Vs* under this respect and is still based on the fundamental insight of the basic feature approach. To recall, according to this approach verisimilitude depends on how much true information h provides about the basic features of the world. Until now, we have worked with a "categorical" notion of information: h provides information about $\pm a_i$ just in case h logically entails $\pm a_i$; otherwise, h doesn't provide any information at all. Such notion, however, is too restrictive: intuitively, it is clear that, for instance, $p \vee q$ does provide at least some information about p, although not so much information as that provided by p itself. On the contrary, definition (3) implies that $p \vee q$ provides zero information about p, exactly as a tautology does: in short, a categorical account of information is too crude to deliver a fine grained definition of verisimilitude. To this purpose, we need a more graded, non-categorical notion of information, according to which the information provided by h on $\pm a_i$ is just the degree to which h entails $\pm a_i$. Such notion of "partial" information is introduced in the next subsection.

3.2 Verisimilitude as partial information about the basic features of the world

Recalling that $\pm a_i : m(\pm a_i|h) > \frac{1}{2}$ is the set of partial basic consequences of h, a simple definition of the amount of information provided by h about each of its partial basic consequences is the plain difference $m(\pm a_i|h) - \frac{1}{2}$. Intuitively, such difference measures the "distance" between the conditional logical probability $m(\pm a_i|h)$ and the absolute logical probability $m(\pm a_i)$. By multiplying the above expression by 2, one obtains the normalized measure

$$inf_i(h) = 2 \times (m(\pm a_i|h) - 1/2) \tag{11}$$

Note that $inf_i(h)$ is always positive and takes 1 as maximum value, when h entails $\pm a_i$.[9] By summing up the information provided by h about each of its partial consequences, one obtains the total amount of information provided by h on the basic features of the world, which can be normalized dividing by n:

(12) $$inf(h) \equiv \frac{1}{n} \sum_{\pm a_i \in b(h)} inf_i(h)$$

Again, one can easily see that $inf(h)$ varies between the minimum information provided by a tautology and the maximum information provided by a constituent:

(13) $$inf(\top) = 0 \leq inf(h) \leq 1 = inf(z_i)$$

Let us now denote $b_T(h) = b(h) \cap T$ the class of basic truths partially entailed by h, and $b_F(h) = b(h) \cap F$ the class of basic falsehoods partially entailed by h. Then, the amount $inf_T(h)$ of true partial information provided by h about the n basic features of the world is defined as:

(14) $$inf_T(h) \equiv \frac{1}{n} \sum_{\pm a_i \in b_T(n)} inf_i(h)$$

i.e., as the normalized amount of information provided about the basic truths partially entailed by h. Similarly, the amount $inf_F(h)$ of partial false information provided by h about the n basic features of the world is defined as the normalized amount of information provided about the basic falsehoods partially entailed by h:

(15) $$inf_F(h) \equiv \frac{1}{n} \sum_{\pm a_i \in b_F(n)} inf_i(h)$$

It should be clear that the above definitions are structurally identical to those given in the previous section for the categorical case (in particular, definitions (12), (14), and (15), on the one hand, are the counterparts of definitions (3), (5), and (6), on the other hand). For this reason, it is not surprising that similar considerations can be repeated here for the case of partial information. First, it is easy to see that $inf(h)$ is the sum of the true and false information provided by h:

(16) $$inf(h) = inf_T(h) + inf_F(h)$$

9 Indeed, in this case, the partial information provided by h reduces to the categorical one (see definition 1). However, according to definition (11), h provides some partial information about $\pm a_i$ also when h entails neither a_i nor $\neg a_i$.

Second, one can again obtain from (16) a definition of verisimilitude simply by changing the sign in the right side of the equation:

(17) $$vs(h) \equiv inf_T(h) - inf_F(h)$$

In words, the verisimilitude of h is the difference between the amounts of partial true and false information provided by h.[10] The following two equalities are the counterparts of equations (9) and (10):

(18) $$vs(f) = -1 \leq vs(h) \leq 1 = vs(t)$$

(19) $$vs(\top) = 0$$

As before, these equalities mean that $vs(h)$ varies between a maximum given by the verisimilitude of the truth and a minimum given by the verisimilitude of its specular. Moreover, the verisimilitude of a tautology discriminates between those h for which the amount of partial true information exceeds the amount of partial false information, and hence $vs(h) > 0$, and those for which the opposite is true, and hence: $vs(h) < 0$.

Table 1 displays the degrees of verisimilitude of the 16 propositions of our toy example in Figure 1, as measured by both Vs and vs (and assuming that $p \wedge q$ is the truth in L_2).[11] Note that the two measures agree on all the conjunctive

Table 1. The verisimilitude of the 16 (logically distinct) propositions of L_2 as assessed by measures Vs and vs, assuming that $p \wedge q$ is the truth. True propositions are on the left, their false negations on the right.

	h	$Vs(h)$	$vs(h)$		$\neg h$	$Vs(\neg h)$	$vs(\neg h)$
1	$\top$	0	0	9	$\bot$	0	0
2	$p \vee q$	0	0.33	10	$\neg p \wedge \neg q$	−1	−1
3	$p \vee \neg q$	0	0	11	$\neg p \wedge q$	0	0
4	p	0.5	0.5	12	$\neg p$	−0.5	−0.5
5	$\neg p \vee q$	0	0	13	$p \wedge \neg q$	0	0
6	q	0.5	0.5	14	$\neg q$	−0.5	−0.5
7	$p \rightarrow q$	0	0	15	$\neg p \vee \neg q$	0	0
8	$p \wedge q$	1	1	16	$\neg p \vee \neg q$	0	−0.33

10 As an immediate consequence of equalities (16) and (17), we find again that $vs(h)$ can be expressed in terms of $inf(h)$ and $inf_F(h)$ or, alternatively, in terms of $inf(h)$ and $inf_T(h)$: $vs(h) = inf(h) - 2inf_F(h) = 2inf_T - inf(h)$.

11 For completeness, table 1 also includes (in cell 9) the logically false statement $\bot$. According to Popper (1963b, Addendum 3, pp. 393 ff); see also Schurz and Weingartner (2010, sect. 2)),

theories, including the constituents. However, they disagree on the remaining, non-conjunctive theories, since vs is, as desired, more fine-grained than Vs. To be sure, in such a simple language as L_2, this is evident only for statements $p \vee q$ and $\neg p \vee \neg q$ (corresponding to cells 2 and 16 in the table).

By considering slightly more complex languages, however, it becomes clearer that vs is actually an adequate measure of truthlikeness for non-conjunctive theories. A couple of examples will illustrate this point. Assume that $t = a_1 \wedge a_2 \wedge a_3$ is the truth in L_3. Then, as far as disjunctions of basic propositions are concerned, one can easily check that, for instance, the following statements are in increasing order of truthlikeness:

$$
\begin{aligned}
&vs(\neg a_1 \vee \neg a_2) \cong -0.22\\
&vs(\neg a_1 \vee \neg a_2 \vee \neg a_3) \cong -0.14\\
&vs(\neg a_1 \vee \neg a_2 \vee a_3) \cong -0.05\\
&vs(\neg a_1 \vee a_2) = 0\\
&vs(\neg a_1 \vee a_2 \vee a_3) \cong 0.05\\
&vs(a_1 \vee a_2 \vee a_3) \cong 0.14\\
&vs(a_1 \vee a_2) \cong 0.22
\end{aligned}
\tag{20}
$$

Note that, on the contrary, Vs is 0 for all the above statements. The reason, as we said, is that vs, but not Vs, is sensitive also to small amounts of information provided by weak hypotheses on the basic features of the world. For instance, while Vs cannot discriminate between the verisimilitude of $h = a_1$ and that of the slightly stronger hypothesis $g = a_1 \wedge (a_2 \wedge a_3)$ – since one can check that $Vs(h) = Vs(g) = 0.5$, one instead obtains that $vs(g) \cong 0.55 > 0.5 = vs(h)$, i.e., that vs is sensitive to the small increase of true partial information provided by g over h.

contradictions should have the minimum degree of verisimilitude; measure vs instead assigns them an intermediate degree of verisimilitude (i.e., 0), on a par with tautologies. This is because both tautologies and contradictions, for different reasons, don't really provide any information about the truth: the former being completely uninformative, the latter providing exactly the same (maximal) amount of true and false information. Here, we decided not to consider contradictions as really relevant hypotheses, in line with much discussion on verisimilitude (cf., e.g., Niiniluoto (1987, p. 150)).

4 Concluding remarks

We conclude our discussion by pointing out some general properties of measure vs. As mentioned in Section 2, all post-Popperian accounts of verisimilitude eschew what Oddie (2013, p. 1652) calls "the relative trivialization of verisimilitude for falsehoods", which, as the Tichý-Miller theorem showed, plagued Popper's original definition. Our account is no exception, since it is easy to check that:

$$\text{if } h \text{ and } g \text{ are false, it may be that } vs(h) > vs(g)$$

An example is provided by the first two equalities in (20), which show that $vs(\neg a_1 \vee \neg a_2) \cong -0.22 < -0.14 \cong vs(\neg a_1 \vee \neg a_2 \vee \neg a_3)$. More interestingly, vs also avoids "the absolute trivialization of verisimilitude for falsehoods" (Oddie, 2013, p. 1652), i.e., it meets the following condition:

$$\text{if } h \text{ is false and } g \text{ is true, it may be that } vs(h) > vs(g).$$

As an example, $vs(a_1 \wedge a_2 \wedge \neg a_3) \cong 0.33 > vs(\neg a_1 \vee a_2) = 0$. Another attractive aspect of vs is that it does not satisfy the implausible condition that verisimilitude increases with logical strength among falsehoods:

$$\text{if } h \text{ and } g \text{ are false, and } h \vDash g, \text{ it may be that } vs(h) < vs(g).$$

The first example given above illustrates also this point: $\neg a_1 \vee \neg a_2$ is stronger, but less verisimilar, than $\neg a_1 \vee \neg a_2 \vee \neg a_3$. More generally, as we said, f is the least verisimilar statement of the language and, at the same time, it is as strong as any other falsehoods can be. In particular, f is stronger but less verisimilar than the negation of the truth, i.e., of the false content element of the language: in our example in L_3, we have that $vs(f) = vs(\neg a_1 \wedge \neg a_2 \wedge \neg a_3) = -1 < -0.14 \cong vs(\neg a_1 \wedge \neg a_2 \wedge \neg a_3) = vs(\neg t)$.

Finally, and quite surprisingly, vs violates the weak value of content for truths, i.e., the condition, discussed in Section 2.3 above, according to which verisimilitude increases with logical strength among truths. In fact, it is easy to check that:

$$\text{if } h \text{ and } g \text{ are true, and } h \vDash g, \text{ it may be that } vs(h) < vs(g).$$

An example is again provided by the equalities in (20): $vs(\neg a_1 \vee a_2) = 0 < 0.05 \cong vs(\neg a_1 \vee a_2 \vee a_3)$. The circumstance that vs violates the weak value of content for truths has several interesting implications that, due to space limitations, we cannot explore here. Following Popper (1963b), many other theorists regard this condition as an important desideratum for verisimilitude; see, for instance, Niiniluoto (1987, p. 133) and Schurz and Weingartner (1987, p. 49), Schurz and Weingartner (2010, p. 417). Still, this desideratum is violated by the well-known Tichý-Oddie "average" measure of verisimilitude, and indeed by all "likeness" accounts as characterized by Oddie (2013, p. 1668 ff.). Here we can only anticipate that this striking similarity between *vs* and the average measure is by no means a coincidence, since, in spite of their completely different conceptual foundations, these two measures of verisimilitude are indeed identical.[12]

12 For a proof of this claim see Cevolani and Festa (unpublished).

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