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An Information Analysis of the 'Physical Object' Concept in Copernican Revolution

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Abstract: The concept of information was introduced in the middle of the last century by Shannon and since then an entire branch of research has been developing into what is called Mathematical Theory of Communication which deals with studying the amount of information exchanged in a communication channel. In this article we want to use the concept of information to analyze the conceptual change that occurred with the Copernican Revolution, limiting ourselves to the concept of Physical/Celestial Object and using the Dynamic Frames developed by Barsalou in Cognitive Science.

Keywords: Information, Dynamic Frame, Copernican Revolution

1. Information

Information is a concept whose meaning we have not recovered from ancient philosophy or Christian theology, but it is a purely modern concept; hence the difficulty in its definition and the multiple meanings that have been assigned to the concept. Shannon (1993) for example highlights this difficulty in the following way: "[…] It is hardly to be expected that a single concept of information would satisfactorily account for the numerous possible applications of this general fields".

Information is usually associated with something independent of the user, which has semantic content (has a meaning), and which is transmitted through multiple means (texts, websites, maps...).
It is usually conceived in terms of "data + meaning" and Floridi (2010) gave a general definition by stating that σ – the basic unit of information (*infon*) – is an instance of semantic information if it consists of data that is correctly formatted and has meaning. Information is therefore composed of data, but is not determined only by them; so, what is their role? To better understand these aspects, let's consider the following simple example: let's examine a page of a book written in an unknown language and notice that we are in possession of some data without meaning; if we delete half the page, we will have half the amount of data but still no meaning; even if we leave just one symbol on the page, we still have data – a small amount – and always no meaning. In these three cases we are in possession of data that is not significant and therefore we have no information. If we now delete the last symbol and leave the page completely blank, we are in the presence of data (the empty page), but with a meaning (the page has no semantic content); the latter case provides us with some information even if it seems like we don't have any data available. Information is therefore not linked only to the presence of data, but is rather conceived as a lack of uniformity, as Bateson (1973) reminds us, when he asserts: "In fact, what we mean by information [...] is a difference which makes a difference".

1.1 Semantic Information

When it comes to the concept of information, we are usually dealing with the Statistical Theory of Information proposed by Shannon, but it – as its name states – has to do with the statistical properties of the information transmitted in a communication channel. Shannon's theory does not deal with the most significant aspect of the term information, namely its semantic content. The first to address the problem from this point of view were Carnap and Bar-Hillel (1953) and, since then, the theory they developed has been called semantic theory of information.[1] In both theories information is defined in terms of a certain concept of probability:

$$inf(\sigma) = -\log(p(\sigma))$$

where $p(\sigma)$ represents the probability of the *infon* σ[2] and from it, it is possible to obtain the concept of entropy associated with information:

$$H = -\Sigma_\sigma\, p(\sigma)\, inf(\sigma)$$

where the summation is done on each individual *infon*. Although the two theories use the same mathematical structure, the concept of probability on which they are based is different: in statistical theory – where we are interested in repeatable situations in the long term – a frequentist interpretation of probability is presupposed, while in semantic theory – in which we are interested in the different alternatives that are made available to us by language – we use a logical interpretation of probability[2] (Hintikka 1970). To assign probability to the different alternatives made available in a certain linguistic context it is necessary to identify some principle that facilitates us in this task; from a heuristic point of view, it can be stated that the more precise a proposition is, i.e. it eliminates any other possibilities, and the greater the information it conveys. This consideration is formalized in the Inverse Relationship Principle, which states that “the ammount of information associated with a proposition is inversely related to the probability of that proposition”. Based on this principle it is possible to define the content of information as:

$$cont(\sigma) = 1 - p(\sigma)$$

which can be easily traced back to the amount of information (*inf*) introduced previously.
Carnap and Bar-Hillel’s semantic theory is based on the principle just described and is developed for monadic first-order logic. In this regard, consider a class of languages, each of which is made up of a finite series of monadic predicates (naming properties), which apply to an equally finite number of individual constants (naming individual) and which can be composed with the usual logical connectors. From a formal point of view, a language is defined as a set $L^n_m = (\{c_1 \ldots c_n\}, \{P_1 \ldots P_m\})$ made up of n individual constants c_i and m predicates P_j. The propositions $P_j\, c_i$ is an atomic sentence and indicates that the constant ci has the property P_j. It is possible to construct an arbitrary number of other propositions, based on the atomic ones and using logical connectors. Of particular importance are those combinations that involve the conjunction of predicates (negated or non-negated) applied to all individual constants in such a way that each constant appears only once in the proposition: such propositions are called state-descriptions (they are usually represented with the letter w). The set of state descriptions constitutes the logical space, and each state description represents a possible state of the world. On the logical space it is possible to define one or more probability measures $m(-)$[3] which are associated with the corresponding confirmation function:

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[1] The Carnap and Bar-Hillel Theory is defined by Floridi as Weak Semantic Theory of Information in contrast to the Strong Semantic Theory of Information proposed by Floridi himself.

[2] Carnap reported the difference in two disjoint concepts of probability: propability$_1$ for the statistical interpretation and probability$_2$ for the logical interpretation (degree of confirmation: a quantitative concept representing the degree to which the assumption of the hypothesis h is supported by the evidence e.)

[3] The choice of the probability measure is determined for example by the symmetric structures that are identified in the logical space (consider for example Carnap’s m* function).

$$c\,(\sigma, e) = \frac{m(\sigma \wedge e)}{m(e)}$$

where e represents the empirical evidence with respect to σ.[4]
To give a concrete example, let's examine a language made up of 3 individual constants and a single predicate, the formalization of which is $L^3{}_1 = (\{a, b, c\}, \{F\})$: the logical space generated by this language is made up of 8 state descriptions (e.g. $w_1 = Fa \wedge Fb \wedge Fc$), each of which has properties $\text{m}(w_\text{i}) = 0.125$, $cont\,(w_\text{i}) = 0.125$ e $\inf\,(w_\text{i}) = 3$ *bit*.

2. Dynamic Frame

The concept of dynamic frame was introduced into cognitive psychology by Barsalou (Barsalou 1992; Barsalou, Hale 1993) and represents a cognitive structure in which conceptual and empirical information are represented in a precise and determined manner. Dynamic frames have been used profitably in the Philosophy of Science to analyze scientific concepts (Kornmesser 2018) and conceptual change (Andersen et al. 2006), but also in the history of science (Gasco 2020).

In short, a frame is an attribute-value matrix that has the task of representing how some characteristics (the values) are the instances of other properties (the attributes). The typical example used to illustrate what a dynamic frame consists of is the one associated with the concept of 'bird', the graphic representation of which is shown in Fig.1. The leftmost element is the concept 'bird' which is called *superordinate concept*; in the central box, there are the attributes {beak, foot} and the values associated with them.[5] The last column of the diagram corresponds to *subordinate concepts* – or derived concepts – which are a specialization of the main concept and activate only certain values.[6] The red arrow, instead, represents a constraint that exists between the 'beak' attribute and the 'foot' attribute. The *constraints* are links that intervene between attributes or between values and the most significant ones are the constraints that exist between values.[7]

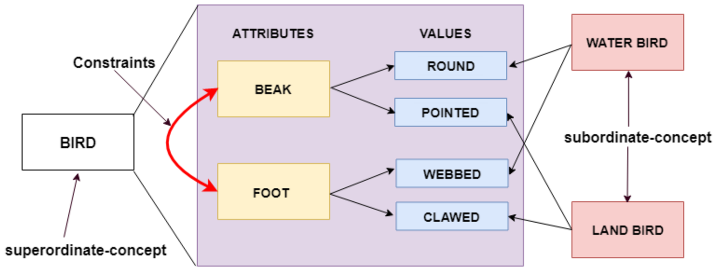

Fig. 1. Dynamic frame 'bird' concept

2.1 Semantic Information of a dynamic frame

Dynamic frames are a structure that can be represented with a first-order formulas (Urbaniak 2009) and therefore the question of associating a quantity of information to the frame arises spontaneously based on the semantic theory of Carnap and Bar-Hillel. The starting point is to show how an attribute of a frame can be represented by a language composed of monadic predicates and individual constants. To do this, consider an attribute $A = (a, (\{V_1{}^a \ldots V_\text{m}{}^a\})$ and note that it can be related to a language $L^1{}_m$ composed of a single individual constant a – the attribute itself – and by m predicates, corresponding to

[4] From now on we will replace the generic *infon* σ with a proposition/hypothesis h linked to the linguistic context being considered.
[5] E.g. the beak attribute has the values {round, pointed}.
[6] E.g. subordinate concepts are "water bird" and "land bird".
[7] E.g. in the case of the subordinate concept 'water bird' there is the constraint that the webbed feet (foot = WEBBED) always correspond to the rounded beaks (beak = ROUND).

the possible values assumed by the attribute. If attribute a has the value V_1, there is a proposition $V_1{}^a a$ which describes its state. The state descriptions that can be obtained by combining the predicates and the single individual constant with the usual logical connectors are $2^{n \cdot m} = 2^m$. However, note that an attribute can take on one value at a time and this limits the number of state descriptions admissible to m; such states are called base-state description and are formally defined as:

$$b_i^a = V_i\left(\bigwedge_{j \neq i} \neg V_j\right)\mathrm{a} = \neg V_1 \mathrm{a} \wedge \ldots \wedge \neg V_{\mathrm{i}-1} \mathrm{a} \wedge V_{\mathrm{i}} \mathrm{a} \wedge \neg V_{\mathrm{i}+1} \mathrm{a} \ldots \wedge \neg V_{\mathrm{m}} \mathrm{a}$$

Therefore, for an attribute we have the relation:

$$A = (a,\ \{V_1{}^a \ldots V_{\mathrm{m}}{}^a\}) \Rightarrow L^1{}_m \Rightarrow \{b^a{}_1 \ldots b^a{}_m\}$$

Finally, if we consider the fact that a frame is a set of attributes, we will have that:

$$\mathrm{F} = (A_1 \ldots A_{\mathrm{n}}) = (a_1,\ \{V_1{}^{a1} \ldots V_{\mathrm{m}}{}^{a1}\}) \ldots (a_{\mathrm{n}},\ \{V_1{}^{an} \ldots V_{\mathrm{r}}{}^{an}\}) \Rightarrow (L_{\mathrm{m}}{}^{a1} \ldots L_{\mathrm{r}}{}^{an}) \Rightarrow (\{b_1{}^{a1} \ldots b_{\mathrm{m}}{}^{a1}\} \ldots \{b_1{}^{an} \ldots b_{\mathrm{r}}{}^{an}\})$$

The state descriptions of the dynamic frame will be the conjunction of the various base-state descriptions of the individual attributes. For example, if we have n attributes, each of which takes on certain values, the generic state description is given by the following formula:

$$w_{V_i^1 \ldots V_k^n} = b_{\mathrm{i}}^{a_1} \wedge \ldots \wedge b_{\mathrm{k}}^{a_n}$$

The set of all state descriptions generates the logical space associated with the dynamic frame. Once the logical space is known, it is necessary to define a probability measure on it. If the constraints between the values are not considered, the state descriptions are equally probable and therefore we have for a generic state $\mathrm{m}\left(\mathrm{w}_{\mathrm{V}_{\mathrm{i}}^1 \ldots \mathrm{V}_{\mathrm{k}}^{\mathrm{n}}}\right) = 1/\mathrm{n}$. However, if we consider the constraints between the values, we can use the confirmation function equation – introduced previously – to impose restrictions on the probability measure. A constraint corresponds to stating that, in the face of evidence in which a certain attribute takes on a certain value ($V_j b$), the hypothesis that another attribute takes on a certain other value ($V_j a$) is certain. In formulas we have[8]

$$\mathrm{h} = \mathrm{V_i a}\ ,\ \mathrm{e} = \mathrm{V_j b} \Longrightarrow \mathrm{c(h, e)} = \frac{\mathrm{m(h \wedge\ e)}}{\mathrm{m(e)}} = \frac{\mathrm{m}\left(\mathrm{V_i a} \wedge \mathrm{V_j b}\right)}{\mathrm{m}\left(\mathrm{V_j b}\right)} = 1.0$$

Once the probability measure on the logical space has been determined, we can calculate the amount of information of a state-description as $inf\,(w_{\mathrm{i}}) = -\log\,(\mathrm{m}\,(w_i))$ and hence the amount of information in the entire frame:

$$inf(F) = \sum_i m(w_i) \cdot inf\big(m(w_i)\big)$$

where index i run on the state-descriptions of the logical space associated with the dynamic frame.

[8] The formula is also valid in the case that, for a given piece of evidence, the probability of a certain hypothesis is zero.

3. The concept of 'Physical Object' in the Copernican Revolution

One of the main innovations of the Copernican Revolution was the elimination of the distinction between celestial and terrestrial objects, which was based on Aristotelian Physics. For Aristotle, the world was made up of five elements (earth, water, air, fire and ether) and the motion of each of them was directed towards its natural place; so for example the earth had the center of our planet as its natural location and its motion was directed towards it. The universe was divided into two macro-regions: the super-lunar world and the sub-lunar world. The first was made up of the ether and included the sphere of the fixed stars and the spheres occupied by the wandering stars, the Sun, and the Moon; it was eternal and was not subject to change. The motion of the objects that made up this portion of the universe was circular, as it was perfect motion, suitable for eternal objects. The sub-lunar world, however, was made up of the other four elements and the natural places were concentric spheres that went from the heaviest element (earth) to the lightest one (fire); the motion of the elements was rectilinear and tended towards the corresponding natural place. The sub-lunar world was subject to change that was determined by the movement of the elements towards their natural place and by the motion of the superlunar spheres which transferred the movement from the sphere of the fixed stars to the lower ones. Following Chen and Barker (2000), the briefly outlined structure is represented in the dynamic frame of Fig. 2. In it we observe how the superordinate concept 'Physical Object' has four attributes that characterize it, each of which can take on two values. There are also constraints on the values (indicated by the red arrows on the left), which indicate the close correlation between the attributes/values; so for example there is a constraint that establishes that if a Physical Object is made up of the ether, then all of its other properties are uniquely determined (the 'location' is 'above Moon', the 'stability' is eternal and the path that takes place in the sky – the path attribute – is circular).

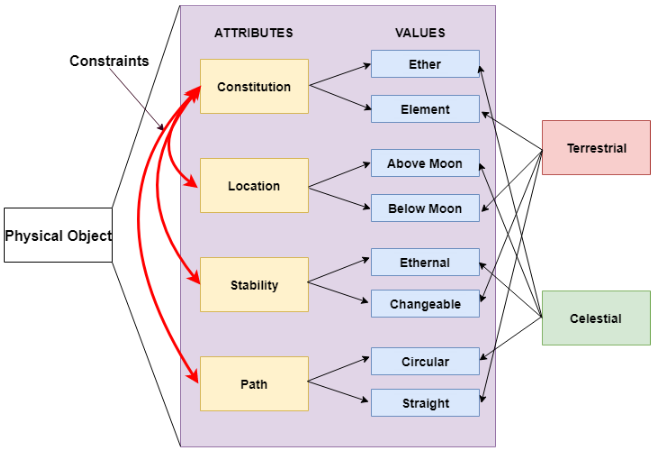

Fig. 2. Dynamic frame of the concept 'Physical Object'

3.1 Semantic Information of the 'Physical Object' dynamic frame

Let us now try to determine the amount of information associated with the dynamic frame of the 'Physical Object'. We observe that the frame has four attributes and is therefore associated with four languages, each of which is made up of an individual constant (the attribute) and two predicates (the values); in this way the relationship holds $phys\_obj = (const, loc, stab, path) \Rightarrow (L_2^{const}, L_2^{loc}, L_2^{stab}, L_2^{path})$. If, for simplicity, we limit ourselves to considering the 'constitution' attribute, we can represent it with language $L_2^{const} = (const, \{Ether, Elements\}) = (c, \{Cet, Cel\})$ formed by the constant c and the two predicates {*Cet, Cel*}.[9] The language generates a logical space made up of two equally probable base-state descriptions on which a probability measure is defined which assigns a value of 0.5 to each state. If we then move on to consider the dynamic frame in its entirety, we have that the total logical space is the conjunction of the base-state-descriptions of the 4 attributes and therefore we generate 16 states.[10] If we do not consider the constraints, the states are equally probable and therefore we are able to define a probability measure:

$$\mathrm{m}(\mathrm{w_i}) = \frac{1}{16}$$

which allows us to determine the information of the entire frame:

$$inf(phys\_obj) = \sum_i m(w_i) \cdot inf\big(m(w_i)\big) = 16 \cdot \frac{1}{16} \cdot 4 = 4bit \text{ }^{11}$$

If instead we consider the constraints, we must use the confirmation function to determine the probability measure. For example, based on the constraints that exist between the values of the attributes, we know that if we examine the evidence $e = (Cet \wedge \neg Cel)c \wedge (Lam \wedge \neg Lbm)l \wedge (Set \wedge \neg Sch)s$ the hypotesis $h = (\neg Pci \wedge Pst)p$ is not correct. In this case we have:

$$c(h, e) = \frac{m(w_2)}{m(w_1) + m(w_2)} = 0 \Rightarrow m(w_2) = 0$$

If we now consider all the constraints present in the frame, we have that the only two states with a non-zero probability measure are those that identify the two subconcepts, to each of which we associate probability 0.5. With these considerations we finally arrive at the quantity of information associated with the concept 'Physical Object' also considering the constraints:

$$inf(phys\_obj) = \sum_i m(w_i) \cdot inf\big(m(w_i)\big) = 2 \cdot \frac{1}{2} \cdot 1 = 1bit$$

We have therefore obtained a significant result: in a dynamic frame the presence of constraints on the values assumed by the attributes decreases the amount of information necessary to define them.

3.2 Criticism of the 'Physical Object' during Copernican Revolution

The concept of 'Physical Object' based on Aristotelian physics was questioned during the Copernican Revolution, weakening some constraints especially thanks to some experimental observations. Of particular interest is the *constitutio ⇒ location* constraint, which was called into question by some observations of comets by Tycho Brahe, which demonstrated that some objects believed to be terrestrial were located above the position of the Moon. We will see later that Brahe's criticism modified the concept of 'Physical Object' from a structural and semantic point of view (for further details see Barker & Goldstein 1988). The first theory of comets was proposed by Aristotle and claimed that they are terrestrial objects belonging to the sphere of fire; comets are transitory and not eternal objects, they change their appearance from night to night and are masses of incandescent vapours. As regards their origin, Aristotle believes that they are formed in the transition from the sphere of air to that of fire, or

[9] The name of the predicates is the composition of the first letter of the attribute (in uppercase) followed by the first two letters of the value assumed by the attribute (in lowercase).

[10] An example of base-state description is $w_1 = (Cet \wedge \neg Cel)c \wedge (Lam \wedge \neg Lbm)l \wedge (Set \wedge \neg Sch)s \wedge (Pci \wedge \neg Pst)p$

[11] The information of the single state is $inf(w_i) = -\log\big(m(w_i)\big) = 4bit$

when the sphere of fire meets the sphere of the Moon. Aristotle's theory of comets was considered congruent throughout antiquity and much of the Middle Ages. In the late Middle Ages, one of the natural philosophers who was most interested in comets was Toscanelli who made numerous observations on them (1433-1472); initially he was interested in their shape but later he focused on their position obtaining measurements compliant with the Aristotelian theory (comets are inside the sphere of the Moon). In 1531 Regiomontanus again dealt with comets and introduced the parallax method – in particular freeing it from cosmological considerations – to study their position, again obtaining results compatible with Aristotle's theory. Regiomontanus also introduced doubts about the constitution of comets, stating that "no irruption of air can supply, from natural causes, flaming vaporous material for the comet for a period of one year; but comets come from secret causes of nature [...]", a consideration which in any case weakens the constraints of the Aristotelian frame. Finally, Tycho Brahe, based on the methods developed by Regiomontanus, experimentally demonstrates that the position of comets is beyond the sphere of the Moon. Following the criticisms of the concept of 'Physical Object' we can now build a new dynamic frame by eliminating the constraint between 'constitution' and 'location': its diagram is shown in Fig.3.

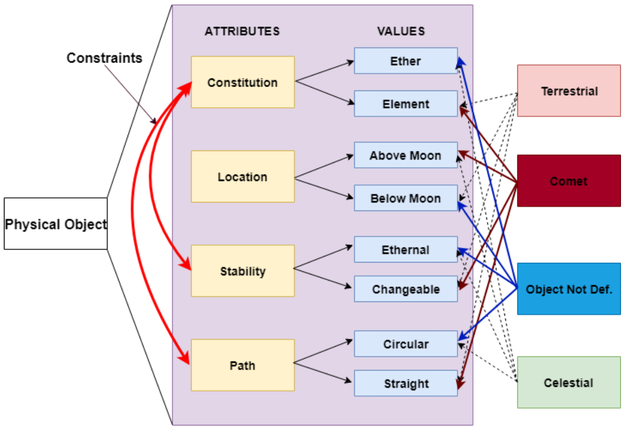

Fig. 3. Dynamic frame of the concept 'Physical Object' during Copernican Revolution

Notice how in the frame there is a greater number of subconcepts compared to the Aristotelian frame: for example, there is the subconcept of comet which has the particularity of being a terrestrial object whose position is beyond the sphere of the Moon.[12] The logical space of the dynamic frame is still made up of 16 state descriptions, but the probability measure has changed and leads to states with non-zero probability:

$$m(w_1) = m(w_{16}) = m(w_5) = m(w_{12}) = \frac{1}{4}$$

Where the state w_{12} corresponds to the subconcept 'comet'. If we calculate the amount of information in the new frame we obtain:

$$inf(phys\_obj) = \sum_i m(w_i) \cdot inf\big(m(w_i)\big) = 4 \cdot \frac{1}{4} \cdot 2 = 2bit$$

which shows how the new dynamic frame needs a greater amount of information to be defined.

[12] There is also an undefined (or experimentally not identified) object, which has the characteristic of being a celestial object but whose position is below the lunar sphere.

4. Conclusion

In this article we presented a formalism that allows us to associate a quantity of semantic information with a dynamic frame and observed how the elimination of constraints between values determines a greater quantity of information necessary to define the frame. We later applied this formalism to an important concept of Aristotelian physics which underwent a profound modification during the Copernican Revolution.

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