A keyword-driven approach to science

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To a good extent, words can be understood as corresponding to patterns or categories that appeared in order to represent concepts and structures that are particularly important or useful in a given time and space. Words are characterized by not being completely general nor specific, in the sense that the same word can be instantiated or related to several different contexts, depending on specific situations. Indeed, the way in which words are instantiated and associated represents a particularly interesting aspect that can substantially help to better understand the context in which they are employed. Scientific words are no exception to that. In the present work, we approach the associations between a set of particularly relevant words in the sense of being not only frequently used in several areas, but also representing concepts that are currently related to some of the main standing challenges in science. More specifically, the study reported here takes into account the words “prediction”, “model”, “optimization”, “complex”, “entropy”, “random”, “deterministic”, “pattern”, and “database”. In order to complement the analysis, we also obtain a network representing the relationship between the adopted areas. Many interesting results were found. First and foremost, several of the words were observed to have markedly distinct associations in different areas. Biology was found to be related to computer science, sharing associations with databases. Furthermore, for most of the cases, the words “complex”, “model”, and “prediction” were observed to have several strong associations.

\section{I. INTRODUCTION}

Since its origins centuries ago as a mostly unified endeavor, science has subsequently branched into a complex hierarchy involving several areas and sub-areas \cite{1}, as a consequence of inevitable progressive specialization required to tackle the growing complexity of several natural world phenomena.

Currently, there is a large number of areas in science and technology \cite{2, 3}, each with its respective focus, which also impacts several other respective characteristics such as the type of approach (e.g. statistic, theoretical, numerical, etc.), employed data (e.g. large databases, simulated, continuous/discrete, etc.), respective dissemination (e.g. books, articles, reports, etc.) and, last but not least, the use of specific concepts and words \cite{4}.

Indeed, as a consequence of the intrinsic differences between the several scientific areas, even the use of more general words and their associations with other concepts can be expected to vary. For instance, take the word \textit{complex}. In areas related to physical science, this concept will likely be more frequently associated with concepts such as information, entropy, and computational cost. On the other hand, the same word \textit{complexity} may relate more frequently with words such as brain, immune system, and animal development in a more biological context.

The intrinsic variation in the use of same words in different scientific and technological areas therefore defines a particularly interesting problem on its own, with potential for contributing not only to a better comprehension of how words are typically used in distinct areas, but also with potential to achieving a more comprehensive understanding of science itself. Several are also the possible more practical applications of a better knowledge about the contextual use of words, such as in devising improved approaches to translation, automated semantic analysis, summarization, among many other interesting possibilities.

An additional result allowed by the study of the specific use of words in different scientific contexts regards the identification of words that are used in more or less uniformly manner within a specific set of scientific areas. For instance, a word that is employed quite differently in diverse areas is more likely to be misunderstood. This type of information also has many other possible interesting applications, such as in identifying words that need to be presented with special care by a given area when trying to address another specific area, or even a multi-disciplinary set of contexts.

The concept of co-occurrence of words is employed in many applications, such as understanding how humans use the words \cite{5, 6} and text classification \cite{7, 8}. By considering standard text classification methods, the counts of sets of consecutive words, called \textit{n}-grams, are frequently employed \cite{10, 12}. Observe that the concept of co-occurrence in these works related to the adjacency of two or more words along the text, while in the present work we take into account the presence of two or more words in a single entry of Wikipedia as a more general indication of their possible relationship.

In approaches based in co-occurrence, \textit{n}-grams have also been employed to assign labels to scientific papers organized into groups according to citations \cite{13, 15}. Furthermore, many studies have dealt with co-occurrence of words by using networks \cite{10}, typically in studies comparing between different writing styles \cite{17, 19} (e.g., analysis of literary movements \cite{17} or different types of text \cite{18}, authorship attribution \cite{19}, among others). More re-
cently, techniques related to embedding \cite{20,22} have con-
considered the co-occurrence of words (e.g., glove \cite{21} and
word2vec \cite{22}).

The present work aims at investigating in a quanti-
tative, objective manner the uniformity/heterogeneity of
the use of specific scientific and technological terms. In-
stead of considering a large number of technical words,
which would constitute an interesting related research
on itself, we focus on a smaller set of terms that rep-
resent some of the main tendencies in science and tech-
nology \cite{24}, namely: “complex”, “database”, “determin-
istic”, “entropy”, “model”, “optimization”, “pattern”,
“prediction”, and “random”. Some other interesting
words, such as causal could not be incorporated be-
cause of the relatively small number of appearances in
the adopted database. Such an approach, focused on
target words, has some interesting advantages while still
allowing a good illustration of the prospect of identify-
ing the usage uniformity. First and foremost, we have
that the results can be discussed individually, therefore
allowing a more substantive and comprehensive analysis
than could be achieved if dozens or hundreds of terms
had been used instead. Then, we have that there are not
so many words that are general enough to be found in
several areas and still have plural interpretations.

We start our analysis by considering only the frequency
of words in the texts. In order to understand the rela-
tionship between words, we considered the co-occurrence
of words. As the next step, we modeled the word rela-
tionships as networks, which are henceforth called colo-
calization networks. From these networks, we analyzed
both the pairwise relationships as well as the groups of
words. Finally, aiming at understanding the relationship
among the areas in terms of these networks, we propose
a method for summarizing the colocalization into a single
network, namely summary network. Many interesting re-
sults were obtained. For example, the word “database”
was found to play an essential role in the area of biology.
In addition, the word “optimization” was identified to
play a central role in the area of computer science and
mathematics, but with markedly different usages. Fur-
thermore, the results corroborated that the words can be
used in different manners depending on the study area.

The remainder of this paper is organized as follows.
Section II A discusses the choice of the employed scientific
terms and fields of knowledge. In the same section, the
dataset and the network model used in the analysis are
described. In Section II B we present the obtained results
as well as their discussion. Finally, in Section IV we present
the conclusions and perspectives of future works.

II. MATERIALS AND METHODS

In this section, we discuss the choice of the analyzed
words and areas. Next, the dataset as well as the em-
ployed methodology for data modeling and analysis are
described.

A. The Selected Words

In the following we provide a brief presentation of the
justification and motivation for the choice of each sci-
etific word, as well as some discussion about their charac-
teristics and relationships with other terms. The main
reference for the choice of this terms, in addition to their
frequent modern usage, stems from the key activities of
predicting and modeling, which forms the basis of the
scientific approach.

Prediction: This corresponds to the main motivation
in science and the scientific method. In other words, the
potential of each developed model ultimately related to
is ability to predict phenomena in the physical world.
Therefore, prediction could be expected to related, in
more general terms, with terms such as model, complex-
ity, randomness, and database. However, these possible
associations can be expected to vary from area to area.
For instance, prediction could be expected to play a more
central role in areas directly related to the physical world,
as physics, neuroscience (e.g., \cite{24}) and biology (e.g., \cite{25}).

Model: Modeling is the principal manner through
which scientists approach natural phenomena in order to
better understand them and make respective predictions.
Though central in science and technology, the relation-
ships of this term are expected to vary in different fields,
as a consequence of the types of models and modeling
approaches. For instance, modeling approaches relying
on large quantities of data, as typically observed in areas
such as neuroscience and biology, are more likely to be
related to terms as databases \cite{26}. Contrariwise, model-
ning approaches in areas as physics and mathematics may
be more closely related to concepts such as optimization
(e.g., \cite{27}).

Optimization: The development of a scientific model
is intrinsically related to the problem of optimization.
Indeed, models are made progressively more accurate
by considering the quality of the respective predictions,
which is therefore optimized. The development of ef-
fective optimization methods, be them of computational
or more general nature, represents a key aspect in sci-
ence and technology given its potential to help solving
several current challenging problems. The role of the
term optimization in different areas is likely to vary as a
consequence of the types of respective data analysis and
modeling approaches.

Complex \cite{28}: One of the greatest scientific challenges
 corresponds to complexity. Though not precisely defined,
complexity subsumes many multiple component systems
undergoing non-linear dynamics. These problems are
challenging not only regarding their theoretical modeling,
but also respective attempts of computational anal-
ysis and simulations. As such, complexity becomes inher-
ently linked to modeling, prediction, entropy, databases,
etc. It is expected that the meaning and relationships
between complexity and other scientific terms will vary
respectively to distinct areas. The importance of com-
plexity is directly reflected in the onset of new areas such


database

colocalization

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both the pairwise relationships as well as the groups of
words. Finally, aiming at understanding the relationship
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a method for summarizing the colocalization into a single
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as complex systems \cite{28} and complex networks \cite{29}.

**Entropy** \cite{30}: Developed independently in statistical physics and information theory, the concept of entropy has attained a central role in science and technology thanks not only to its powerful conceptualization, but also to the many applications that have been respectively motivated. In particular, entropy has been considered as a possible quantification of complexity (e.g., \cite{31}). Given its stochastic nature, entropy is also intrinsically related to randomness. This term is expected to have varying applications and relationships in distinct areas. For instance, as already observed, in physics it will be more directly related to statistical mechanics, being more associated with information in computer science.

**Random**: Most real-world phenomena involves, to some extent, some randomness, may it be associated to measurement accuracy or experimental error. As such, randomness constitutes an important concept in every applied science. The application of this concept in different areas will reflect the accuracy of the experimental data, as well as the types of models adopted for respective explanation.

**Deterministic**: Deterministic opposes randomness. It remains a challenging basic question whether nature is deterministic or not. This terms can be expected to generally relate with concepts such as randomness (by opposition), modeling, database, etc.

**Pattern**: Pattern is a generic name given to basic entities in modeling, corresponding possibly to a signal, an image, etc \cite{32}. Reflecting the human tendency to associate names to most entities, the problem of pattern recognition plays a central role in science and technology, as it is ultimately necessary for the automatizing of most human activities. Generally speaking, the term pattern is therefore expected to relate to random, complex, database, among others, but it is likely to assume specific relationships in distinct areas.

**Database**: Given that scientific modeling relies critically on the comparison of predictions/simulations with real-world quantitative measurements, the importance of the concept of databases has progressively increased, giving rise to research areas such as database \cite{33}, data science \cite{34}, and eScience \cite{35}. Basically, a database corresponds to a logically organized dataset with some minimal quality. This term is potentially related to areas such as pattern, complex and model, but its associations can be expected to vary from an area to another.

### B. The Selected Fields

In order to investigate how the associations between the considered scientific terms vary within distinct fields, it is necessary to select a representative group of these areas. The areas considered in the present work were chosen because, by their own nature, they are likely to incorporate a substantial number of entries related to the selected scientific terms. Thus, we have general areas as biology, mathematics, computer science and physics. In addition, we also adopted some relatively more specific areas — more specifically dynamical systems and neuroscience — because of their potential relationship with the considered scientific terms.

### C. The Dataset

In order to select texts for the considered fields, we considered the Wikipedia \cite{36}, which is a free online encyclopedia created from contributors that maintain the content update. This platform is multilingual, but here we considered only the English version. For each described subject, corresponding to a respective page, there are hyperlinks connecting to other pages. Some subjects are organized into subcategories. Here, we considered the pages cited from the articles listed in the following categories:

- **Physics**: Category:Concepts in physics;
- **Mathematics**: Category:Mathematics;
- **Computer science**: Category:Computer science;
- **Dynamical systems**: Category:Dynamical systems;
- **Biology**: Category:Biology;
- **Neuroscience**: Category:Neuroscience.

Furthermore, all the scientific words shown in Section \ref{sec:1} are considered in this work. Because some words are similar but not exactly the same in the text, before creating the network, the following pairs of words were considered as being the same: “complex” and “complexity”, “model” and “modeling”, “prediction” and “predict”, and “optimization” and “optimize”.

### D. Words colocalization network

We considered a network of co-occurrence of words in texts, which we call *words colocalization network*. Observe that this is different from the standard co-occurrence networks because here the entire documents are considered, and not only the immediate adjacency between words. In other words, two of the considered terms are understood to localize whenever they both occur in a same text. Before creating this network, the texts are pre-processed. First, the part of speech (POS) tags, e.g., nouns and verbs, is identified for all the words \cite{37}. By considering the identified POS tags, we lemmatize all the tokens using Wordnet \cite{38,39}. More specifically, lemmatization consists of the simplification of some words by their respective lemma. For example, the different verb tenses conjugation “study” “studying” “studied” are represented by the same lemma “study”.
The colocalization networks are created by considering all files for each field, where each word represents a node, and the edges are assigned when two words co-occur in at least one file. The weights are computed as the number of files leading to co-occurrence. As with the previous models, the resultant network is weighted and undirected.

### E. Summary network

In order to interpret the relationship between the networks proposed in Section II D, we visualize relationships between the networks, $g_1, g_2, \ldots, g_n$. More specifically, in a summarized version each node represents a network ($g_i$), while the edges are computed according to differences between their respective adjacency matrix. First, the weighted networks are converted to unweighted, according to a given threshold. All the $g_i$ edge weights are normalized by their highest value. The edges with weight lower than a threshold, $\tau$, are then removed. Here, for the considered summarized networks, we empirically define $\tau = 0.5$. Edges are assigned to all possible connections between nodes $i$ to $j$ of the summarized network. Their weights are calculated as the number of the edges of $g_i$ that also take part in $g_j$.

### III. RESULTS AND DISCUSSIONS

This section starts our analysis by considering word counts statistics and the co-occurrences of words in documents. Next, the word and field networks are considered. For all of the analyzed information, we discuss possible relationships between the scientific fields and words.

#### A. Word statistics

We start our analysis by considering the frequencies of words in each of the considered areas (see Figure 1). This figure depicts the absolute value of each word found in each area. So, in general, the areas with bigger texts tend to have the highest frequencies for almost all words. The most frequent word in all areas is model, which evidences its particular importance in science. The second most frequent word is complex, followed by pattern and prediction. In contrast with these results, deterministic resulted in the least frequently used word.

As the next step of the analysis, we compare the co-occurrences within the documents for each of the analyzed areas. Figure 2 displays these frequencies for each word separately. As well as in the previous results, the word model is found to co-occur more frequently. Many results presented here are in accordance with the discussion presented in Section II A. For example, complex is strongly related to model (see Figure 2(a)). In contrast, complex is not found to co-occur with entropy for the analyzed areas.

Interestingly, the word database frequently co-occurs with complex and model in the areas of computer science and biology, as shown in Figure 2(b). For biology, these co-occurrences indicate a less straightforward relationship, highlighting the importance of databases for the development of biology. When considering dynamical systems, as expected, the word deterministic is found to co-occur with model, as illustrated in Figure 2(c). The word deterministic also co-occurs with complex, which can be related to studies regarding complex systems modeling.

Furthermore, except for mathematics, model is found to be related to complex (see Figure 2(d)). As shown in Figure 2(d), entropy is not a frequent word in the considered areas. However, for the area of physics, this word is found to be related to model. The word optimization plays an important role in computer science and co-occur more frequently with complex, model, and pattern (see Figure 2(e)).

The area of neuroscience contains relatively more co-occurrences between pattern and the words complex and model (see Figure 2(g)). Similarly to this result, relationships between the term prediction and the words model and pattern are also found in neuroscience, see Figure 2(h). As illustrated in Figure 2(i), the word random is frequently used in dynamical systems, and always co-occur with complex and model. This result may be related to the fact that, in the dynamical systems, potentially complex models are simulated by considering random variables.
All in all, the obtained results support the fact that a same scientific word can be used quite distinctly in different areas, reflecting their current priorities and specific types of data, methods and modeling.

**B. Words colocalization network**

Further complementary analysis can be obtained in terms of the relationships between words obtained for
each area. In this case, we employ the words colocalization network proposed in Section 11D. The visualization of this network considering all fields is shown in Figure 3. As in the analysis developed in the previous section, the network visualizations display a wide range of connectivity patterns. This result indicates that, for all analyzed fields, the word contexts can differ. For instance, the weights of the connections between model and prediction present a pronounced variation. One strong relationship that was found to be preserved for all networks is between the words model and complex, indicating that complexity can be related to models regardless of the analyzed area.

C. Core relationships

In addition to considering pairwise relationships between words, it is also interesting to take into account the subset of words defined by the more intense relationships. Henceforth, we understand the nodes interconnected by the 6 edges with largest weights as corresponding to the core of each considered area. For instance, in Figure 3(b), which presents the relationships between the scientific words in the area of neuroscience, the words “complex”, “model”, “random”, “pattern” and “prediction” are more strongly interconnected, giving rise to a respective core.

The analysis of these cores provide an interesting perspective from which to better understand the different use and meaning of the considered words in distinct scientific areas, as well as insights about the main current tendencies in each of those areas. In the remainder of this section, we present a discussion about the cores obtained for each area taken into account, which was developed taking into account information about the involved entries.

In the case of biology, we have its core corresponding to the words “complex”, “model”, “pattern”, “prediction”, and “database”. These areas are strongly related to the interface between biology and computer science, being directly associated to the multidisciplinary areas of bioinformatics and systems biology. These words can also be subdivided into two groups, namely “complex”, “model” and “prediction”, which are closely related to modeling and the scientific method, and “pattern” and “database”, which are characteristic of pattern analysis and data science. The union of these two subgroups are part of the scaffolding of bioinformatics and systems biology.

The area of neuroscience has a similar core to that found for biology, involving the words “complex”, “model”, “random”, “pattern” and “prediction”, with the word “database” being swapped to “random”. This seems to reflect the fact that randomness is relatively more frequently associated to the other core words than the database. Also, observe that the pattern of interconnection between these words is distinct from the previous case, with the words “complex”, “model”, and “pattern” being more strongly interrelated. To a great extent, this core also reflects the interface between neuroscience and computer science, being particularly related to the multidisciplinary areas of neuroinformatics and neuromorphic and placing more emphasis on randomness as compared to database. The identification of this particular core indicates that these words are more typically used in associations related to the above discussed interdisciplinary concepts.

The area of physics has its core defined by the words “complex”, “model”, “random”, “prediction”, and “entropy”. This core is very similar to those identified for biology and neuroscience, with the difference that the word “pattern” as being replaced by “entropy”. Again we have a close interrelationship between words directly related to modeling, namely “complex”, “model”, and “prediction”, but now entropy assumes a more prominent role, reflecting the importance of this concept in the area of physics.

The core identified for the area of dynamical system includes the words “complex”, “model”, “random”, “deterministic”, and “prediction”. The words “complex”, “model”, and “prediction” again indicate a strong emphasis on modeling and the scientific method, but now we have a new substantial relationship also with the word “deterministic”, which indicates that the other words are often being employed while discussing the key issue of a system being (or not) deterministic, which is reasonable given the importance of this concept in the area of dynamical systems.

The area of mathematics resulted with respective core incorporating the words “complex”, “model”, “random”, “pattern”, and “optimization”. Three words present particularly strong interrelationship, namely “complex”, “model”, and “optimization”. This indicates emphasis on the concept of optimization, which is indeed a recurrent subject in mathematics. The word “pattern” tends to be associated with the word model, indicating that its main usage could be related to the complexity of patterns in abstract and physical worlds.

The core obtained for the area of computer science includes the words “complex”, “random”, “pattern”, “database”, and “optimization”. In particular, we observe the absence of the word “model”, which appears in all the other areas considered in the present work. Again, we observe that the world complex is particularly associated to “pattern”, which could be related to areas such as computational complexity and pattern generation or recognition. “Optimization” also presents a strong relationship with the word “complex”, suggesting associations with the area of computational optimization.

D. Summarized network

In order to better understand the relationship among the networks presented in Figure 3, we created the summarized network (see Figure 4). As can be seen, the
FIG. 3. Colocalization networks, in which the nodes represent the adopted words, and the edge widths the percentage of documents in which the pair of words co-occur. The edge connecting “model” and “complex” in item (c) corresponds to the maximum obtained co-occurrence, which represents 25% of the articles.

relationships between the analyzed terms vary. The edge between some pairs of fields are not shown because that relationship is too small, which reinforces the idea that the words tend to be employed in different manners for each analyzed field.
IV. CONCLUSIONS

In writing and speaking, words are used to communicate insights and pieces of information. However, a same word can have different meanings depending on its context, such as the area in which it is employed. In order to better understand this interesting phenomenon, we study some particularly some relevant scientific words ("prediction", "model", "optimization", "complex", "entropy", "random", "deterministic", "pattern", and "database") respectively to some major areas of study ("biology", "neuroscience", "physics", "dynamical systems", "mathematics", and "computer science"). These areas were analyzed by considering pages obtained from Wikipedia.

Aiming at understanding the relationship between the selected scientific words, we considered a network where the nodes represent words and the edges are weighted according to the colocalization of the words in the entire entries, i.e. when two words appear in a same Wikipedia page.

Many interesting results were obtained. In general, the relationships between fields were shown. For example, the word "prediction" was found to be related to "model" and "complex". However, the relationship with "random" was not observed. Relationships between "complex" and "database" were also expected for most fields. However, it was found only for the areas of computer science and biology. As expected, the word "model" turned out to be related to "database" in biology and neuroscience, but these relationships are not too strong in comparison with others, mainly for neuroscience. The word "optimization" was found to play an important role in the area of computer science. This word was also observed to be strong in the area of mathematics but, in this case, the contexts are different. The relationship between "entropy" and "complex" and "random" was found for the field of physics. Since the word "entropy" is intrinsically related to information theory, we expected that this word could play an important role in computer science, which was not the case. For all considered fields, the word "deterministic" was not observe to be strongly related to other words but, as supposed, though it resulted being moderately related to "random". Many relationships could also be expected to be obtained between the word "pattern" and the words "model", "random", "complex", and "database". In the case of the latter, its relationship with the word "pattern" was verified only for the area of computer science.

By defining a core for each of the colocalization networks, it was possible to discuss relationships between the considered scientific areas. Surprisingly, the areas of biology and computer science were found to be similar when considering the relationships of the words "database" and "prediction". This result illustrates the proximity between these fields, which relates to the field of bioinformatics. Furthermore, the relationships indicate that these words tend to have similar meanings in both areas, which allows the researchers to communicate with particular effectiveness among themselves.

Taking into account that the context is essential to the solution of tasks related to natural language processing (e.g., text classification, authorship attribution, and sentiment analysis), our study paves the way for future studies. As future works, other scientific words and fields can be studied. Furthermore, our analysis can be considered in order to incorporate more relevant information, such as in embedding techniques.

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