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Nanotechnologies — Methodology for the classification and categorization of nanomaterials

Nanotechnologies — Méthodologie de classification et catégorisation des nanomatériaux

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Contents

Page

Foreword iv
Introduction v
1 Scope 1
2 Nano-tree structure 1
3 Detailed description of nano-tree 2
4 Conclusion 3
Bibliography 25

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO/TR 11360 was prepared by Technical Committee ISO/TC 229, *Nanotechnologies*.

Introduction

The existence of a wide range of nanomaterials with various physical, chemical, mechanical, optical, magnetic, and biological properties, as well as different internal/external structures, highlights the importance of the design of a classifying system based on which these materials can be logically categorized. This Technical Report offers a comprehensive methodology for the classification and categorization of various nanomaterials. Such a classifying system, here termed the nano-tree, while considering the most basic and common elements as the main trunk of the tree, also differentiates nanomaterials in terms of their internal/external structures, their chemical nature, and their physical, mechanical, biological, and other properties.

The classification and categorization of nanomaterials with a systematic approach containing a logical hierarchy between its various sectors can be of assistance to the wide range of scientific and engineering disciplines engaged in research, industry, and government. Because of different backgrounds and requirements, there can be widely divergent understandings and assumptions associated with emerging scientific concepts. The result can be poor communication, a lack of interoperability among systems, and duplication of effort as groups strive to define concepts and identify standards needs according to diverse perspectives. Public dissemination of the nano-tree is beneficial to industry, consumers, governments and regulatory bodies to promote clear and useful communication. The nano-tree classification system can be used to place nanotechnology concepts into context by indicating relationships among these concepts. Such context provides users with a structured view of nanotechnology and facilitates a common understanding of nanotechnology concepts.

This Technical Report is a depiction of the current understanding of the structure and relationships for an emerging field. It is considered to be a snapshot of the subject domain at a particular time and may be revisited as the domain develops. It presents an illustrative approach to advance communication and understanding, rather than an exhaustive consideration of the possible approaches to classifying nanomaterials. It is not intended to exclude other completely legitimate methods of classification that can be considered now or in the future in the domain of nanotechnology.

This classification of the subject domain of nanotechnology places the domain's concepts into relevant categories and shows the relationships among concepts. The primary utility is in identifying those concepts that help in properly categorizing the subject domain. This system has several purposes. The major aims and capabilities of the proposed nano-tree can be summarized as follows:

a) to provide a basic classification system for different types of nanomaterials;

b) to pinpoint the required standard characterization techniques for the nanomaterials of interest (to be carried out by ISO/TC 229/WG 2);

c) to facilitate the identification of the important characteristics/properties of a specific nanomaterial in scientific journals and patents with the help of a database search engine by providing the necessary keywords for use by ISO/TC 229 Working Groups, including the work of ISO/TC 229/WG 4 on material specifications;

d) to facilitate the design of “nomenclature framework” required for the logical and systematic terminology of nanomaterials.

This Technical Report was developed during the same period as the establishment of terminology hierarchies to guide the creation of definitions in a logical order of priority. Inevitably, this resulted in differing structural representations of the field. The “nano-tree” is constructed to be consistent with the science that underlies nanotechnology, as is made clear in this Technical Report. In contrast, nanotechnology terminology hierarchies are structured as required by the logic of language and by the need for their definitions to be mutually consistent within those structures. Nevertheless, the comprehensive methodology for the classification and categorization of various nanomaterials proposed in this Technical Report is intended to be consistent with the terminology framework of ISO/TC 229. Both approaches have their respective design rules and foundations and both serve aims and needs that differ. Their one common characteristic is that they will both grow over time.

In this Technical Report, there is no intention to define terms in acknowledgement of the parallel, ongoing work in terminology development noted above. Terms approved by ISO/TC 229/WG 1 are shown in italics in Figure 2.

Nanotechnologies — Methodology for the classification and categorization of nanomaterials

1 Scope

This Technical Report describes a classifying system, termed a “nano-tree”, upon whose basis wide ranges of nanomaterials can be categorized, including nano-objects, nanostructures and nanocomposites of various dimensionality of different physical, chemical, magnetic and biological properties.

However, the classifying system presented in this Technical Report does not claim to provide full coverage of the whole range of nanomaterials.

2 Nano-tree structure

Considering the undeniable role of dimension on the various properties of these materials, the nano-tree presented here utilizes dimension as the basic element of classification in the first step. Based on the literature review carried out in References [1] to [10], the assignment of dimension in nanomaterials can be considered by two alternative methodologies:

a) one based on spatial dimension;

b) one based on quantum confinement (QC).

The methodology based on spatial dimension considers any external dimension of the material in the nanoscale (between 1 nm and 100 nm) as a dimension, while the dimensions greater than 100 nm are not considered. Therefore, for example, if two external dimensions of a material are in the nanoscale and the third is greater than 100 nm, the material is considered to be a two-dimensional (2D) material.

The methodology based on quantum confinement considers the fact that whenever the size of a solid material becomes comparable to the wavelength of the particles that interact with such a system, a free carrier will be confined. Such a system is referred to as “quantum confined”.

It should be mentioned that both of these methodologies have some advantages and disadvantages when compared to each other. For example, in case of the quantum confinement model, the determination of dimension requires information on electron wave function behaviour that is normally not readily available outside the scientific community. On the other hand, the assignment of the exact size below which the quantum confinement behaviour dominates in different materials is not an easy task. Moreover, applying this methodology for complex nanomaterials such as nanocomposites or mesoporous films and layers may be difficult. Based on this model, the interpretation of zero-dimension for quantum dots is more feasible.

For the dimension methodology, although the above-mentioned difficulties do not present themselves for the assignment of dimension, such a system does not realize the very important effect of quantum confinement which has an undeniably remarkable effect on the various properties of nanomaterials. The dimension approach is the preferred method chosen in this Technical Report. It is again necessary to mention that the nano-tree presented here may not include the whole range of nanomaterials, but with the systematic approach utilized in this classification system, it is possible to develop and apply additional steps to the current method to fulfil this very important task.

Figure 1 illustrates the various parts of the nano-tree. As shown in Figure 1, it consists of four major columns. Following the classification of various nanomaterials based on their dimensions in the first column, these are subsequently divided based on their internal/external structures in the next column. Further, in the next step, these are divided according to their chemical nature/identity followed by their various behaviour and properties (e.g. electronic, chemical, mechanical, biological). It should be added that information concerning the commercial applications that are possible for particular nanomaterials based on their exhibited properties could be fully developed in a similar nano-tree format.

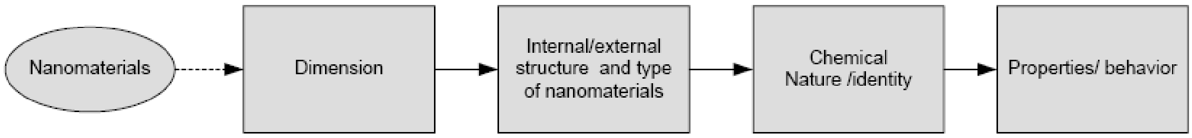


Figure 1 — Simplified sketch of the nano-tree based on dimension approach

3 Detailed description of nano-tree

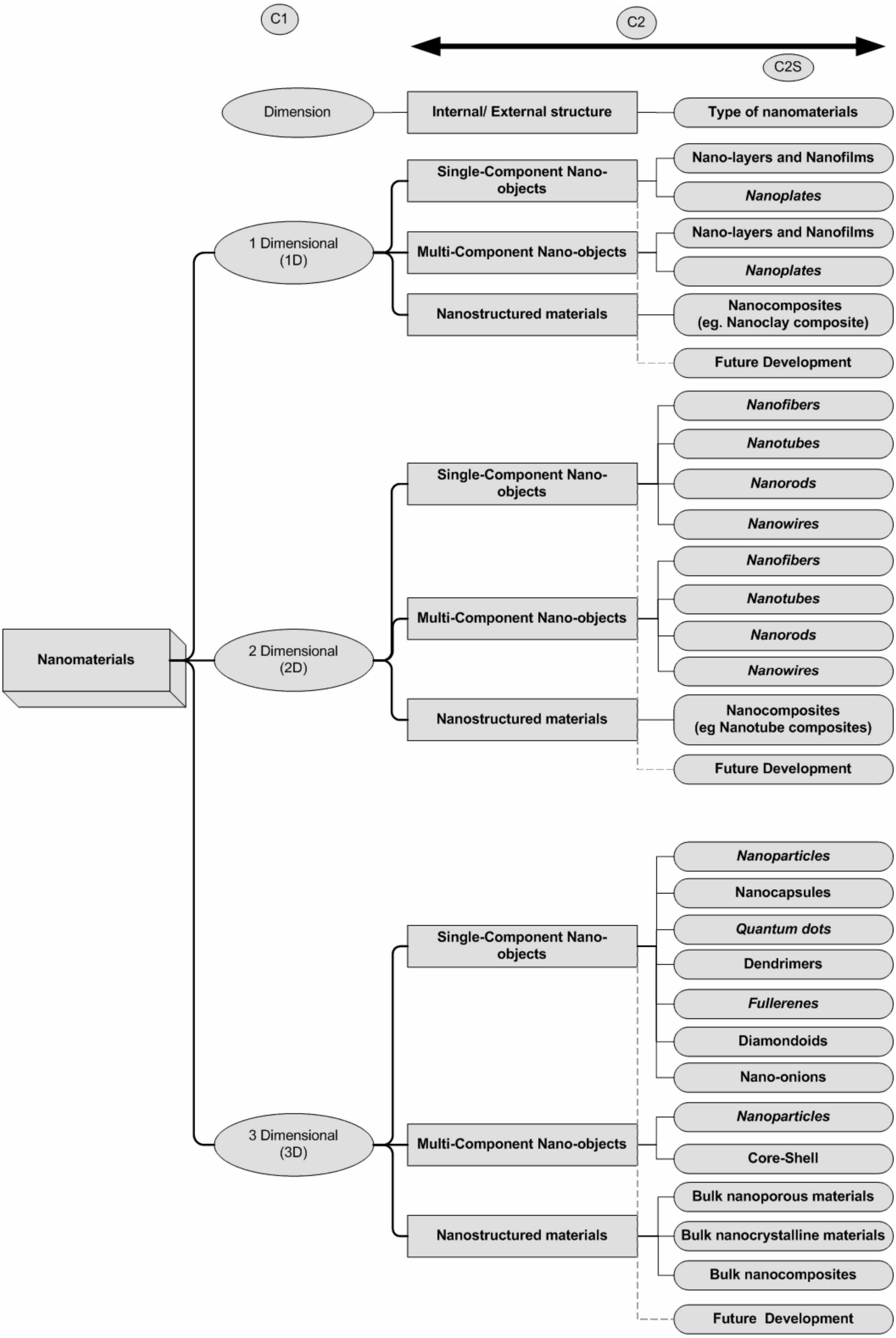
Figure 2 illustrates the first two constituting columns (presented as C1 and C2) for the nano-tree. In the C1 column, nanomaterials are classified as 1D, 2D and 3D's. In the C2 column, each of these is subdivided into single- or multi-component nano-objects or nanostructured materials. Here, a multi component nano-object is referred as an object composed of areas or regions with identifiable, local, chemical and structural fluctuations. Further, 1D, 2D and 3D nanostructured materials may also refer to nanostructures composed of 1D, 2D and 3D nano-objects or containing a quantity of discrete nanoscale features. Moreover, various types of nano-objects and nanostructures are presented in their assigned positions in the next sub-column, C2S, in Figure 2. The cases shown here are simply limited, typical examples of how the columns are populated. For future developments, a representative box is used to satisfy this aim (dotted lines are used in the nano-tree to signal areas of potential expansion to take future developments into account). Moreover, as already mentioned, based on the dimension methodology (D), the differentiation between 1D, 2D and 3D nano-object is size-related. In this respect, for the sake of simplification, other cases (such as a 2D nanoplate or 3D nanotubes) are not shown in the nano-tree at this stage.

Figures 3 and 4 also demonstrate the columns C3 and C4 of the nano-tree, respectively. As shown in Figure 3, column C3 is devoted to the classification of previously subdivided nano-objects and nanostructures based on their chemical identity/nature. In this respect, they are sub-grouped as metallic, ceramic, synthetic or natural polymers, semi-metallic, carbon-based and organic (see Figure 3). Such a differentiation highlights the fact that the effect of chemical nature or type of bonding on the overall properties of nanomaterials, in addition to dimension, should not be ignored. It should be mentioned that composite nanomaterials could contain at least two or more components from column C3. In this respect, various types of nanocomposites composed of different types of nano-objects and nanostructures with different dimensionality and chemical identity in a known matrix could be considered as presented by the nanocomposite box in front of column C3. For example, the dispersion of 1D nanoclay (a ceramic nano-object) in a polymer matrix can be considered a 1D ceramic/polymer nanocomposite. In another case, the dispersion of 2D TiO_2 as a ceramic nano-object in an organic matrix (see Reference [11]) can be considered a 2D ceramic/organic nanocomposite. Nevertheless, it is possible that there may be certain materials that the nano-tree, as presently arranged, does not permit to be classified.

The fourth column (C4) of the nano-tree presented in Figure 4 displays the various corresponding physical, mechanical, chemical, biological and combined properties of nanomaterials. These were selected based on their appearance in the literature, an understanding of the properties that are likely to be leveraged or enhanced through nanotechnology, and their relevance to materials science. In this way, key properties can be used to classify a particular nano-object and nanostructure. The physical properties presented for consideration include magnetic, electrical, optical, thermal and acoustic behaviour. Further, the following combined properties are also considered in cataloguing nanomaterials: magneto-optic, electro-optic, piezoelectric, pyroelectric, thermoelectric and electromagnetic behaviour. These aforementioned properties are subsequently further broken down (sub-categorized), based on their various measurable characteristics and parameters. These are presented in Figures 5 to 27. However, the aim of this Technical Report is not to actually quantify each of the individual properties at this time, but rather to classify the nanomaterials themselves. It is acknowledged that a qualitative classification still may often require the development of a common terminology and requisite test methods to enable a classification to be carried out. Even the apparently simple question of how to measure the size of a nanoparticle is very difficult in this context. Thus, appropriate definitions and standardized measurement techniques still need to be developed before the full potential of this classification scheme can be realized.

4 Conclusion

As previously noted, the nano-tree depicts the current understanding of the structure and relationships of and among nanomaterials, and provides a means to classify them. It uses dimension and key functional properties to distinguish nanomaterials from one another and to show relationships. The utility of such a system can be seen, for example, in how it permits one to identify commercial applications that rely on one or more of the property sub-categories to succeed, and pair that knowledge with the type of nanomaterial(s) classified as exhibiting the property or properties. It is also useful in listing the various types of nanomaterials for public understanding of the kinds of products that are being used and considered for standards development. In this way, the nano-tree is also a communication tool. The nano-tree is intended to be revisited and expanded as the domain develops, while not precluding the use of other completely legitimate systems of classification in the domain of nanotechnology.



NOTE Sub-column C2S provides examples of typical nanomaterials that can be classified based on dimension, internal, and external structures.

Figure 2 — Nanomaterial classification columns based on dimension, internal, and external structures

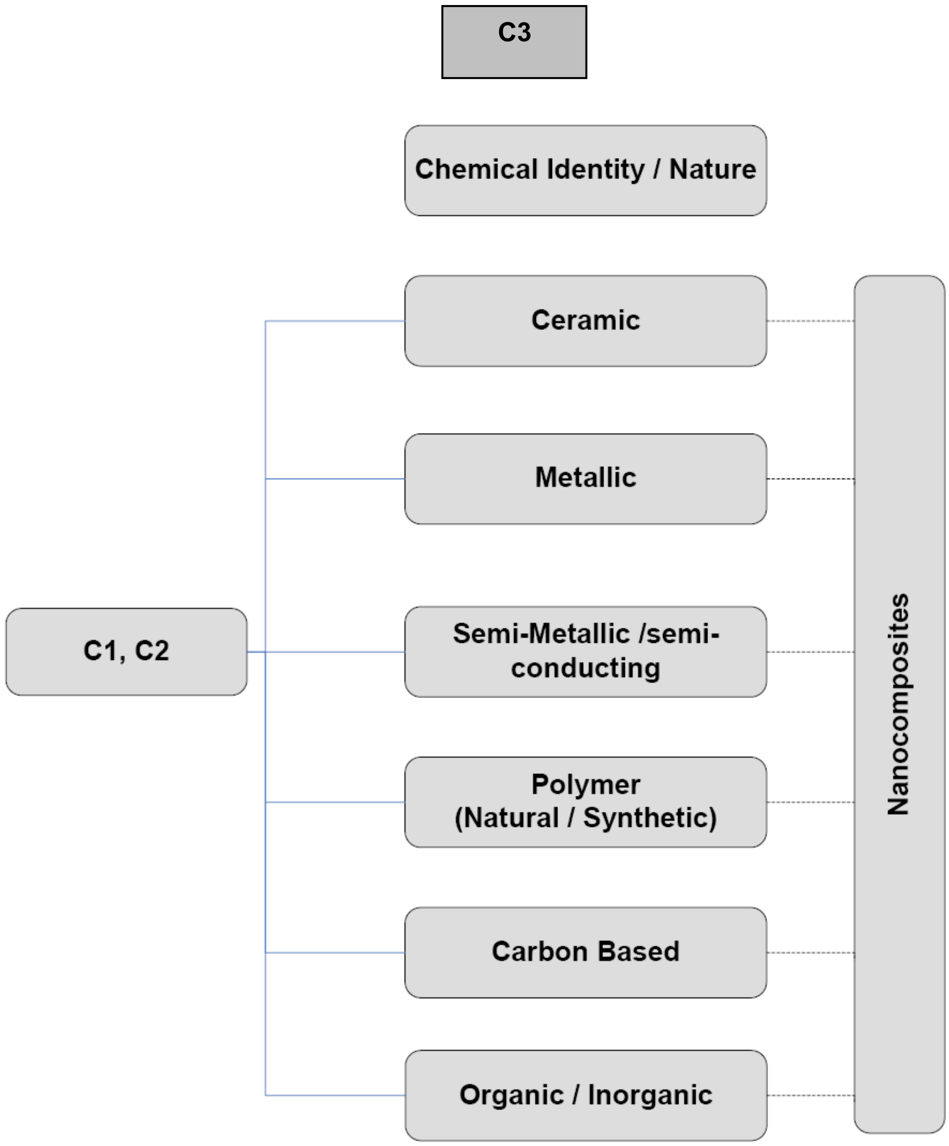


Figure 3 — Further classification of columns C1 and C2 in terms of chemical identify/nature

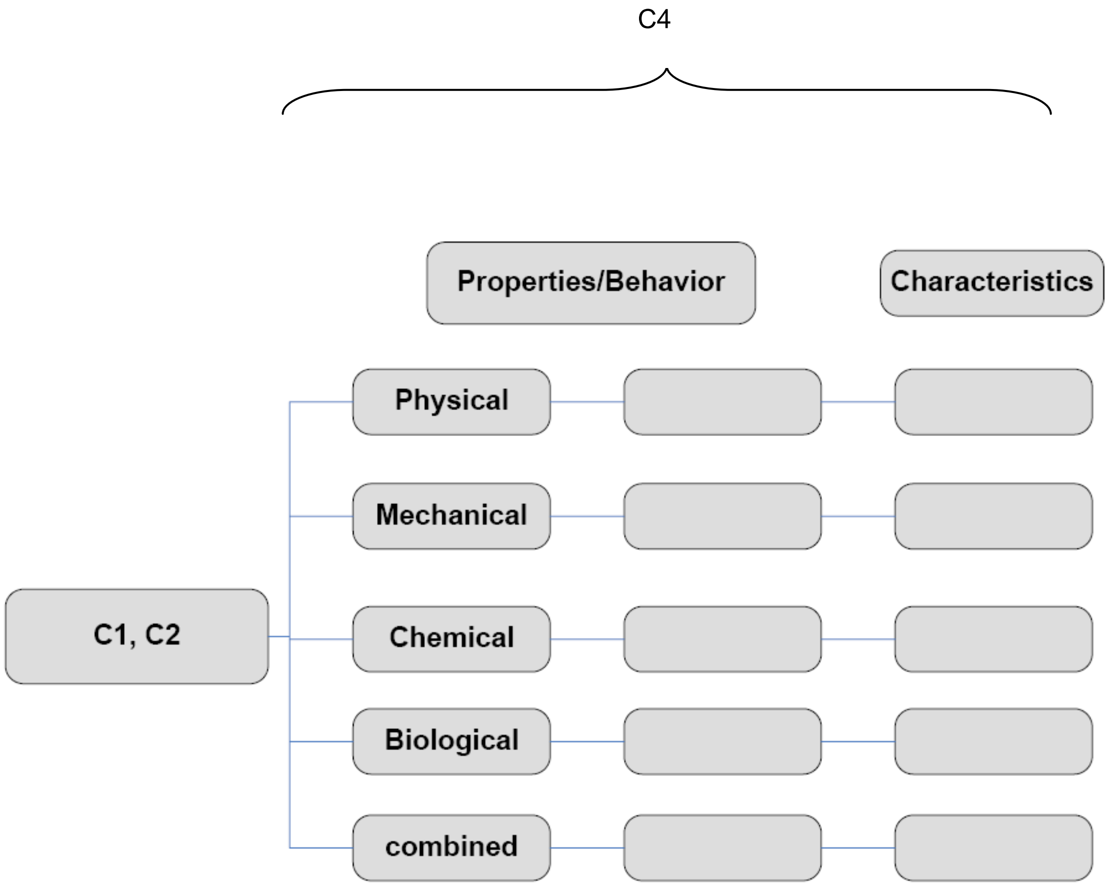


Figure 4 — Further classification of columns C1, C2 and C3 in terms of properties/behaviour and characteristics

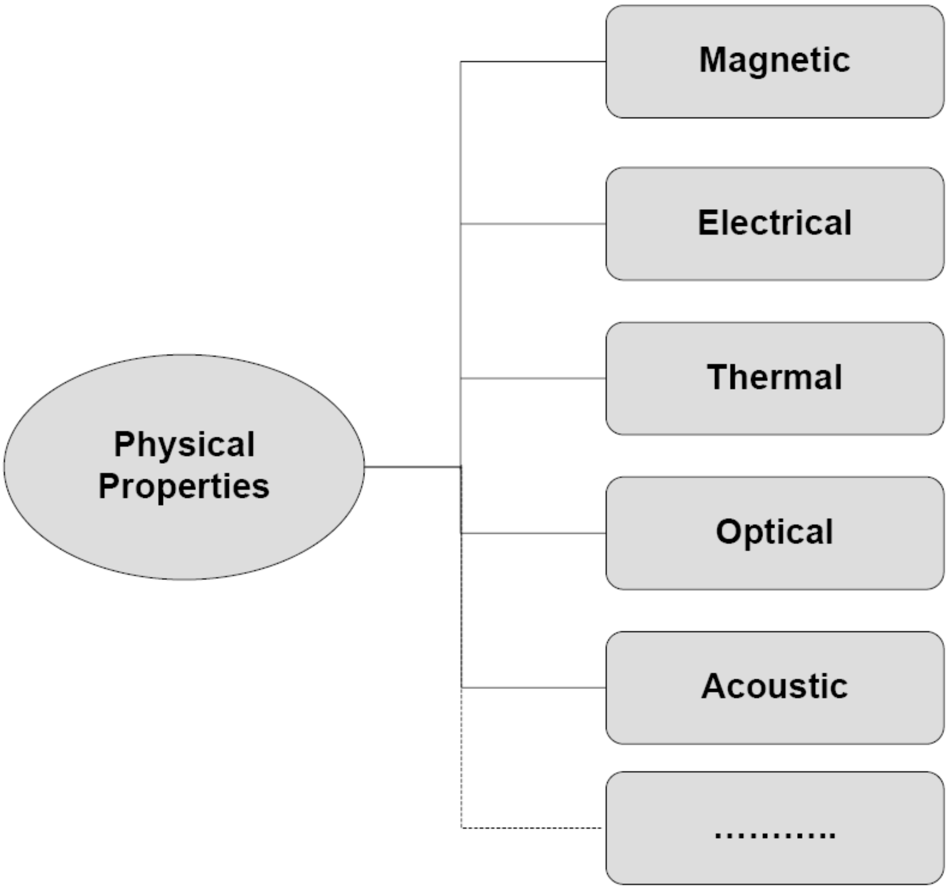


Figure 5 — Classification of physical properties

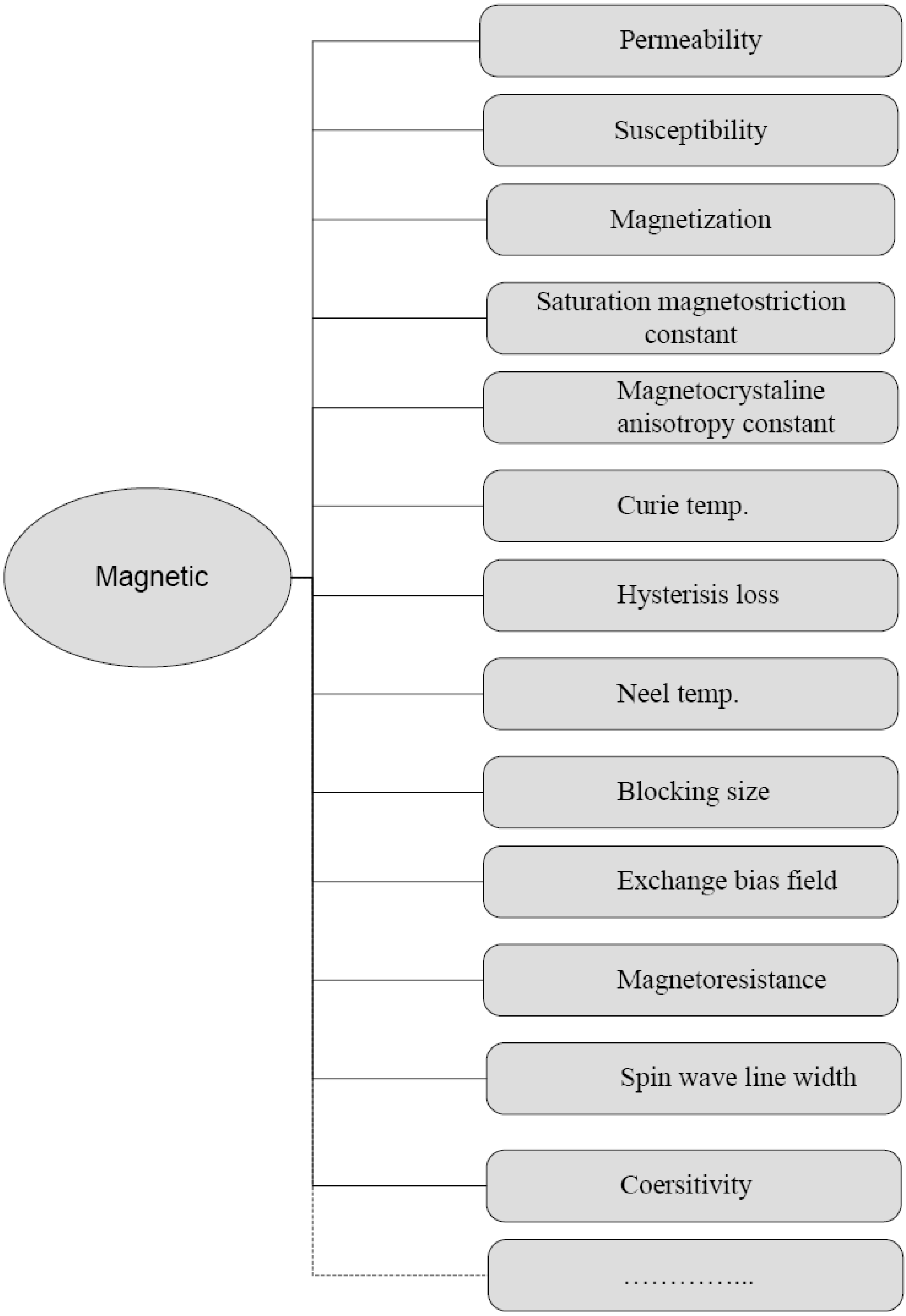


Figure 6 — Classification of magnetic properties

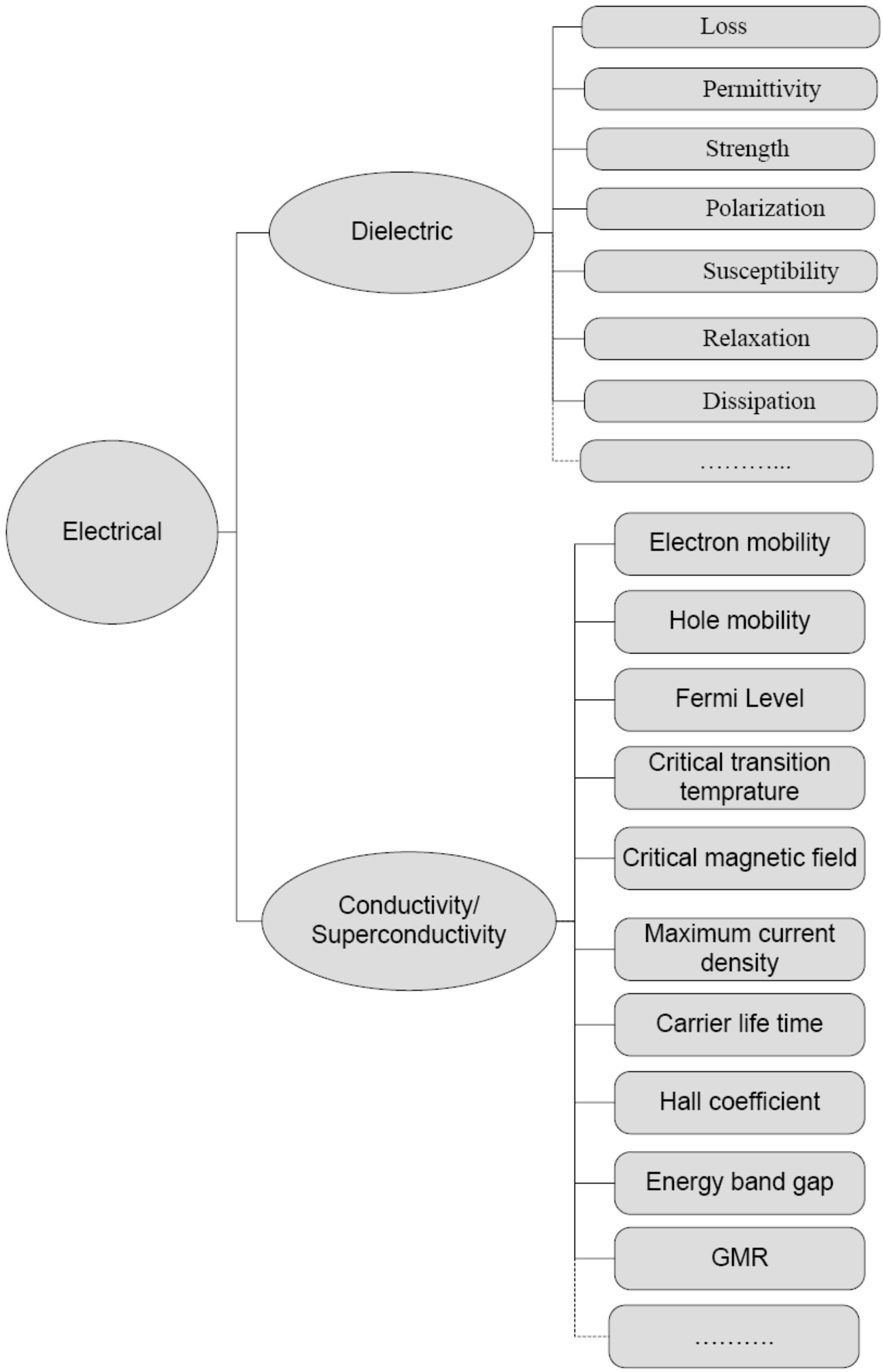


Figure 7 — Different electrical /dielectric characteristics related to electrical behaviour

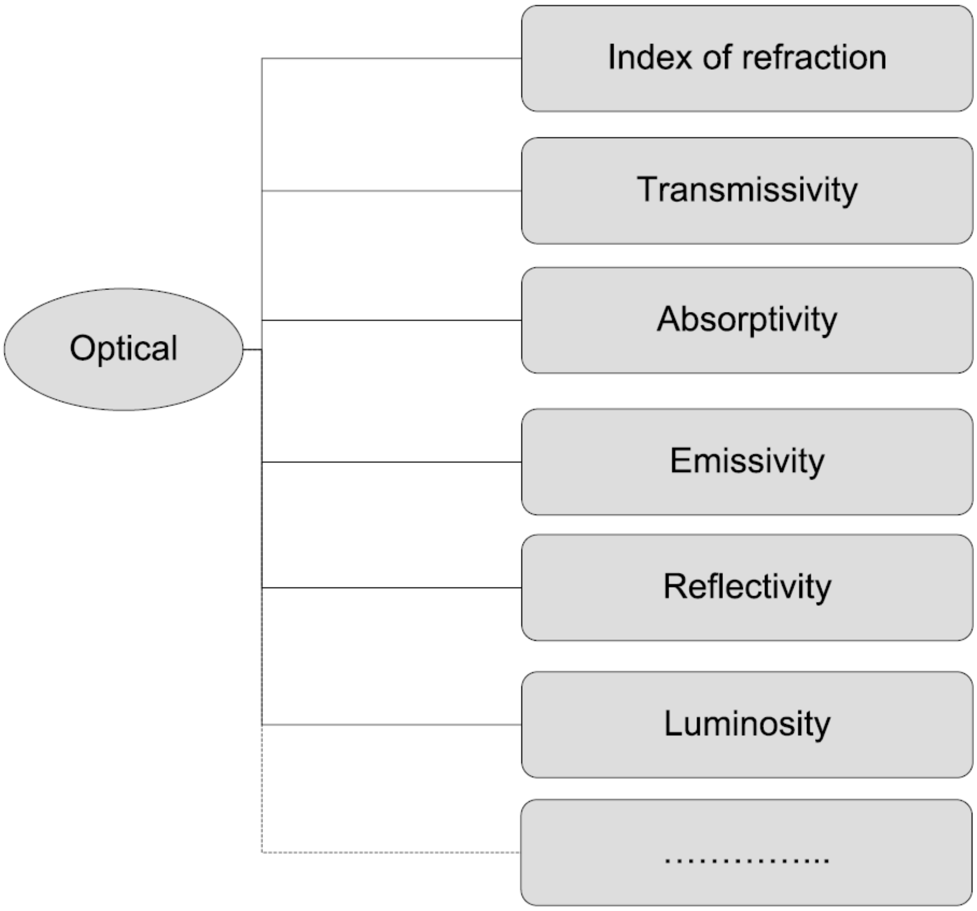


Figure 8 — Classification of optical properties

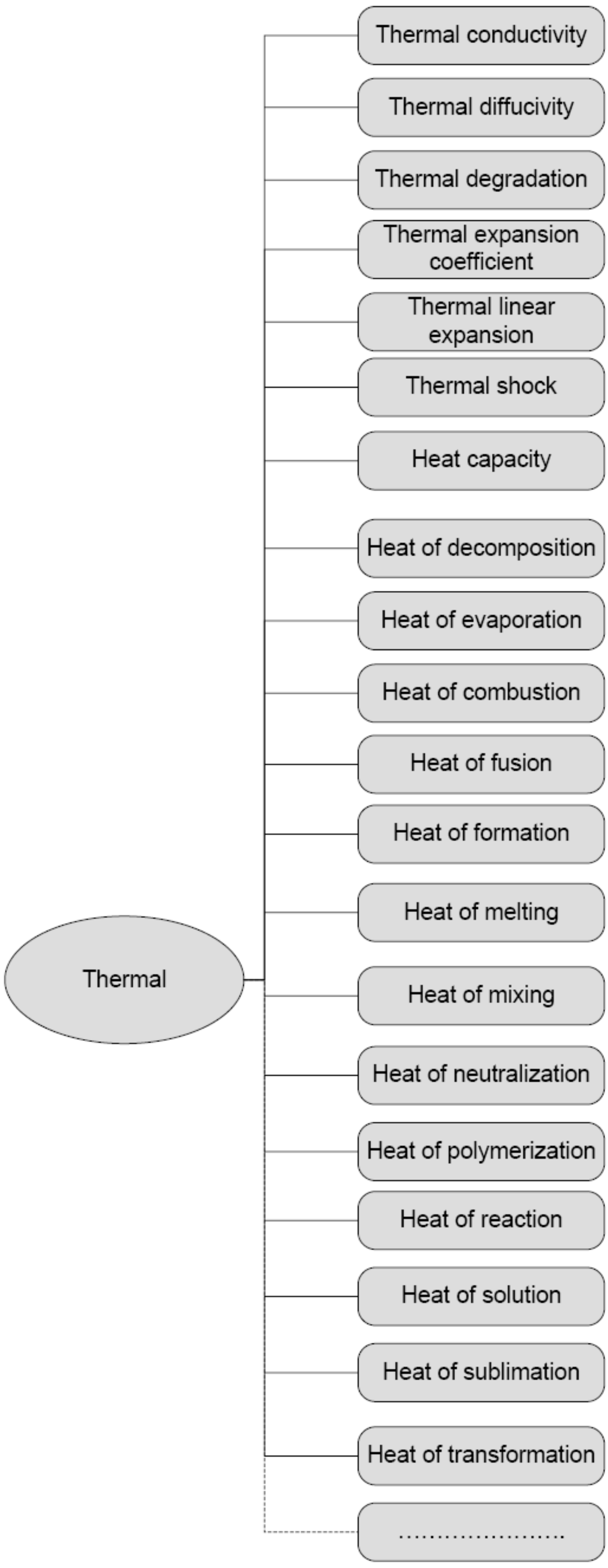


Figure 9 — Classification of thermal property

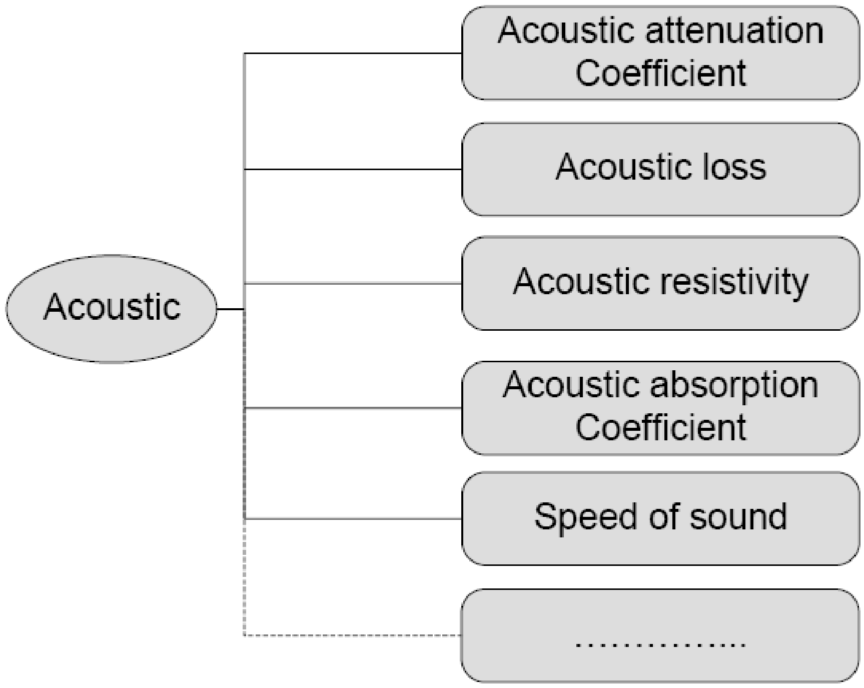


Figure 10 — Classification of acoustic behaviour

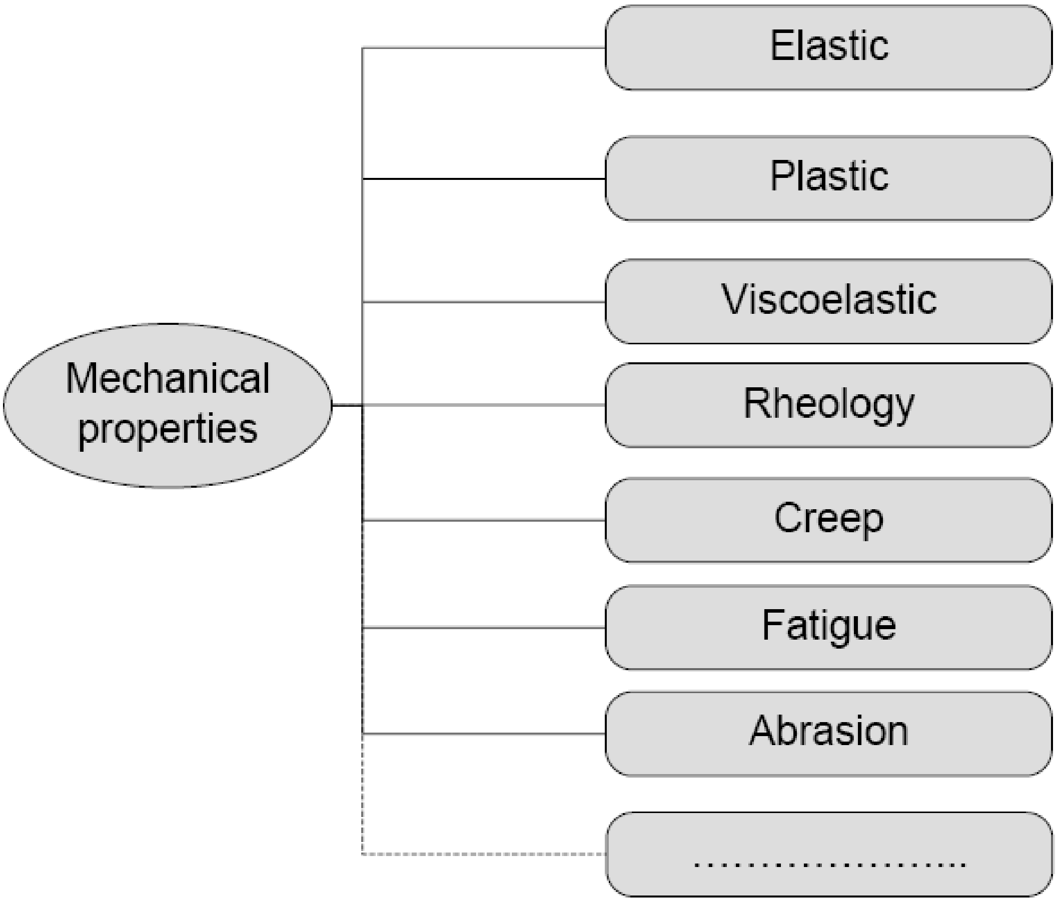


Figure 11 — Classification of mechanical properties

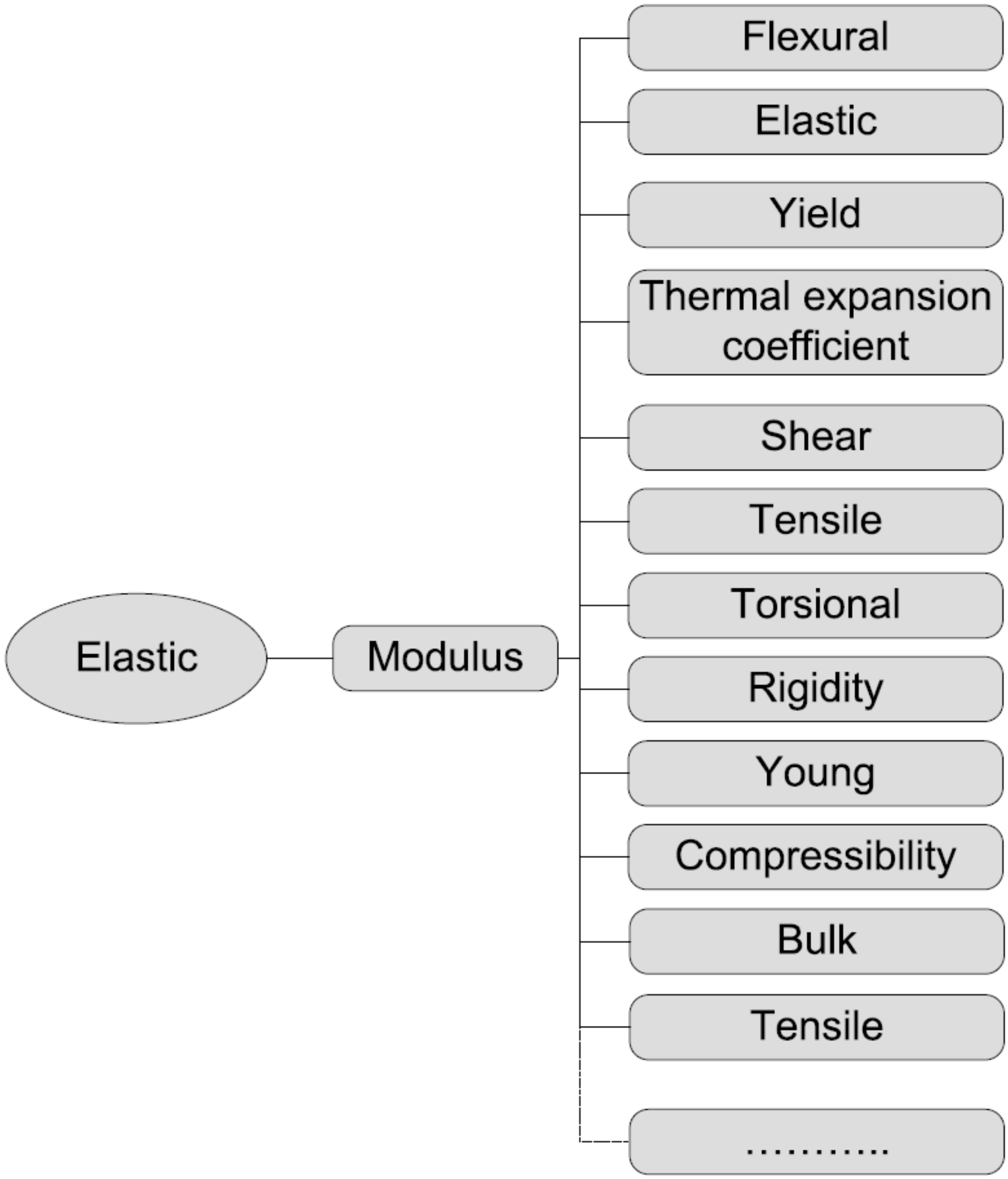


Figure 12 — Classification of elastic behaviour

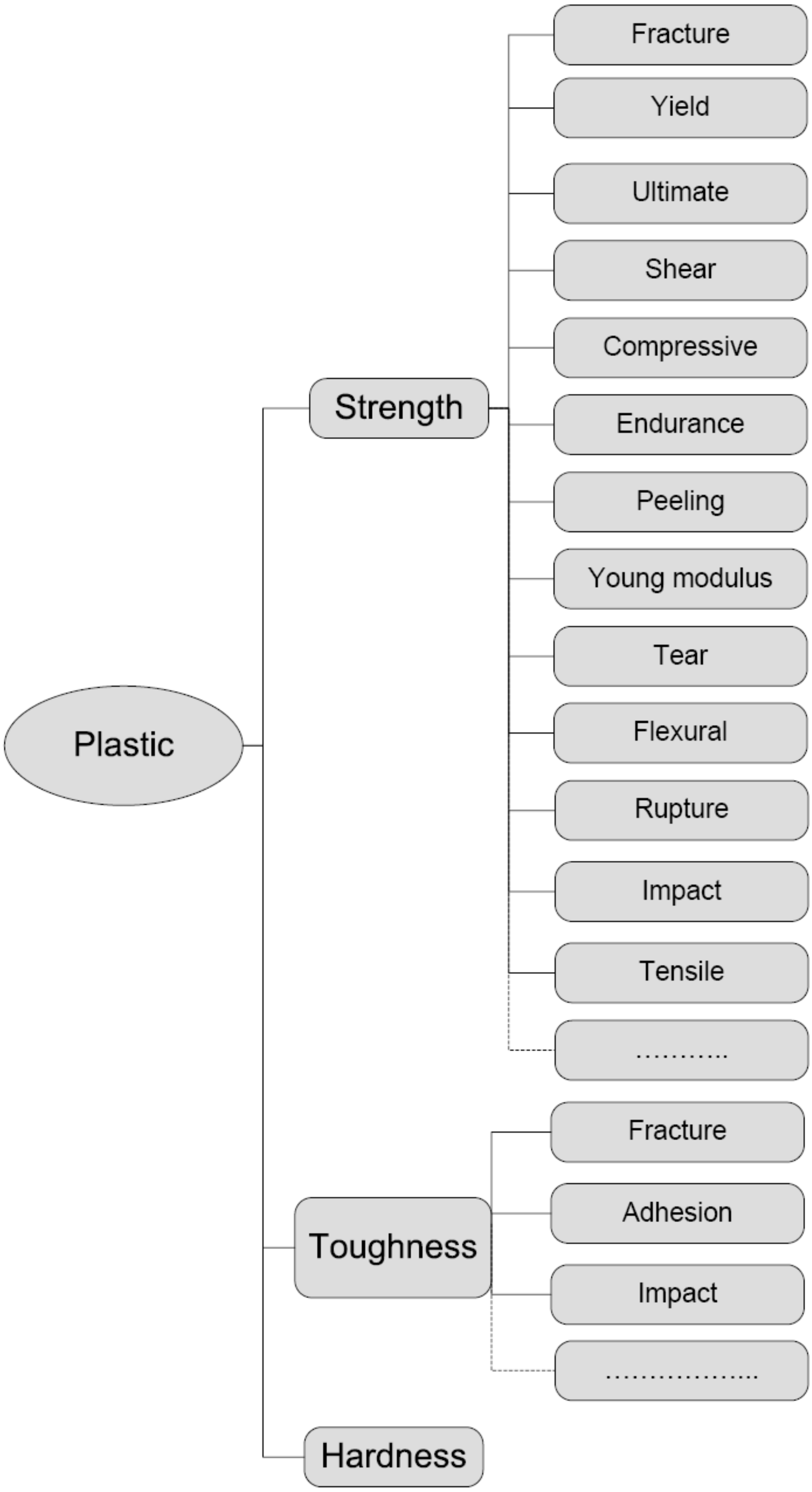


Figure 13 — Classification of plastic behaviour

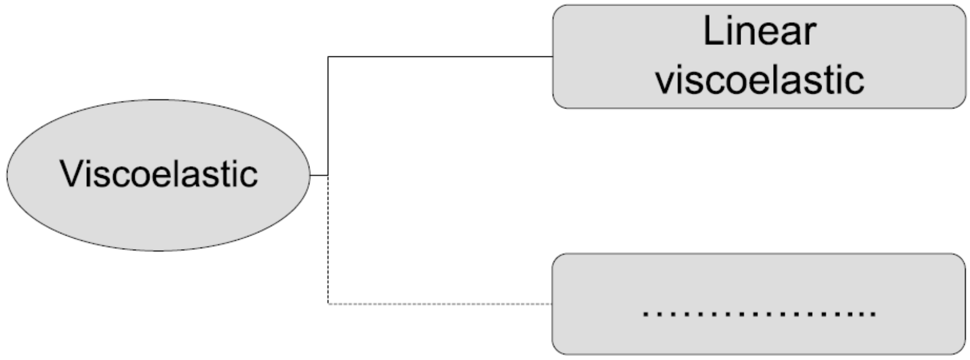


Figure 14 — Classification of viscoelastic behaviour

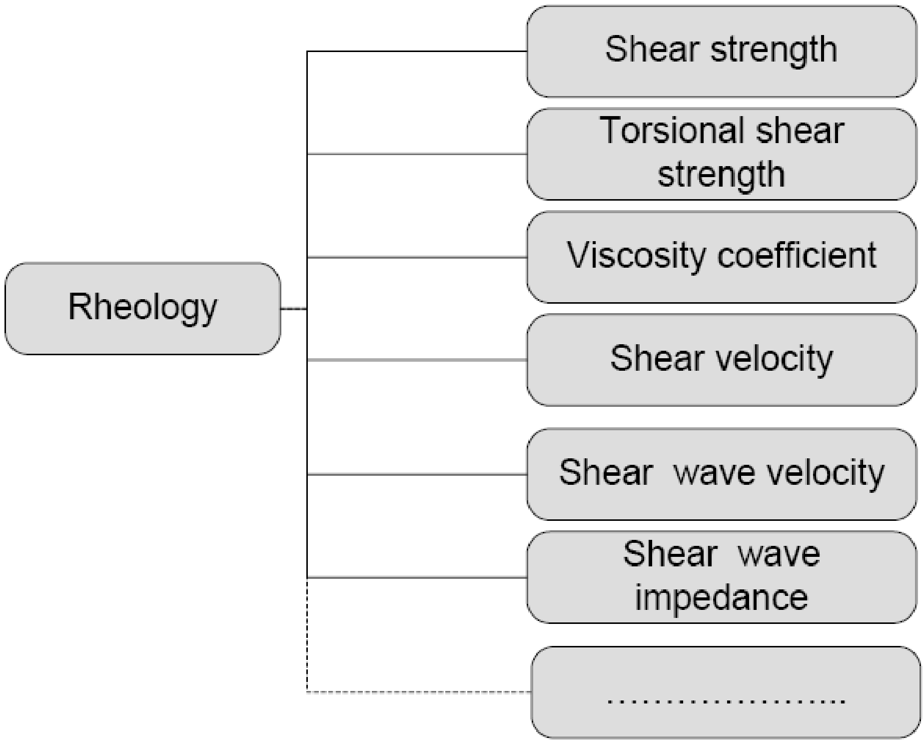


Figure 15 — Classification of rheology behaviour

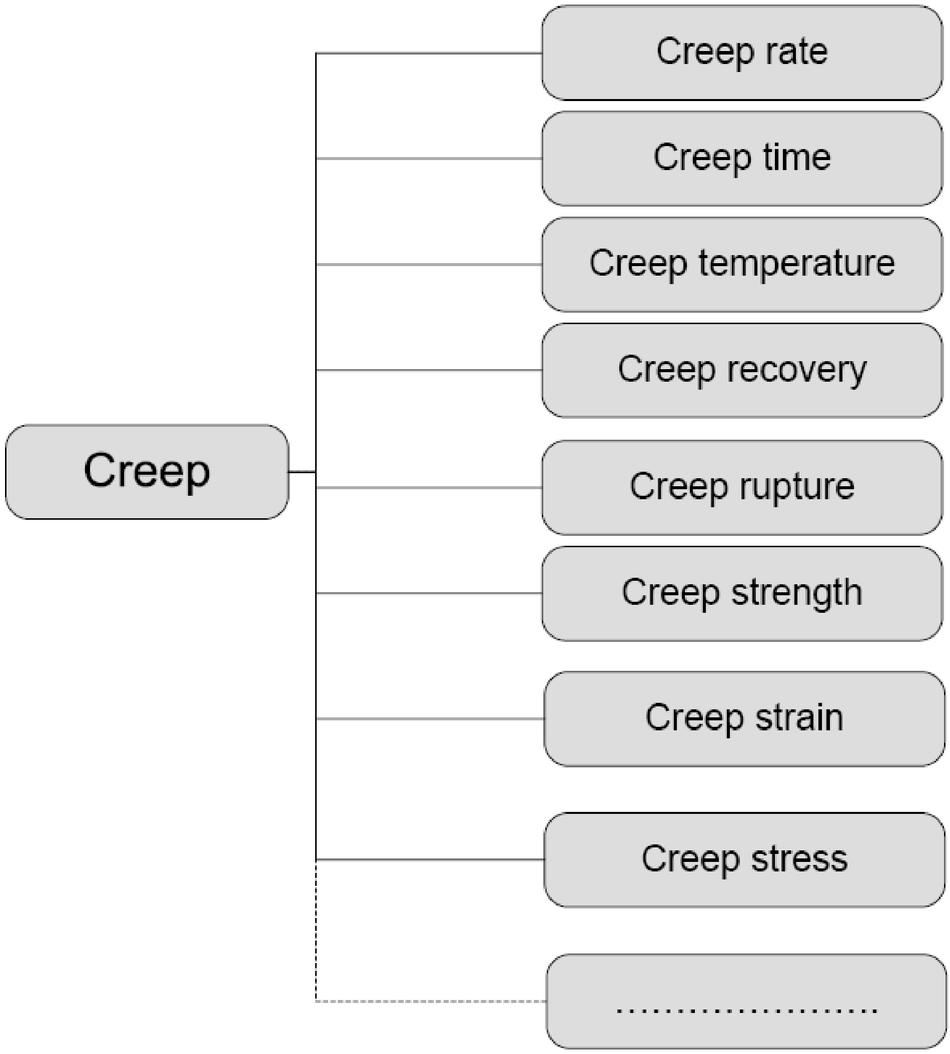


Figure 16 — Classification of creep behaviour in terms of different characteristics

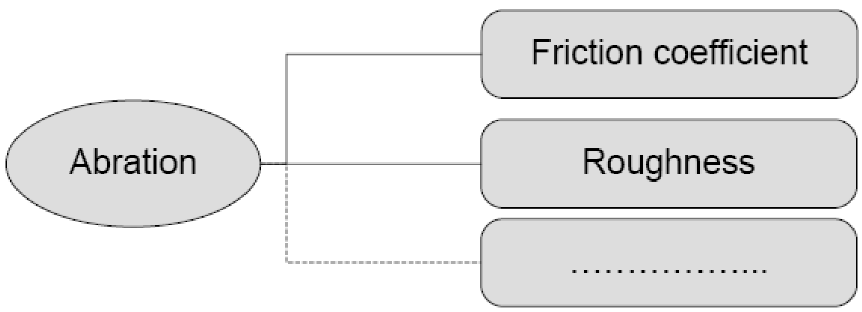


Figure 17 — Classification of abrasion behaviour

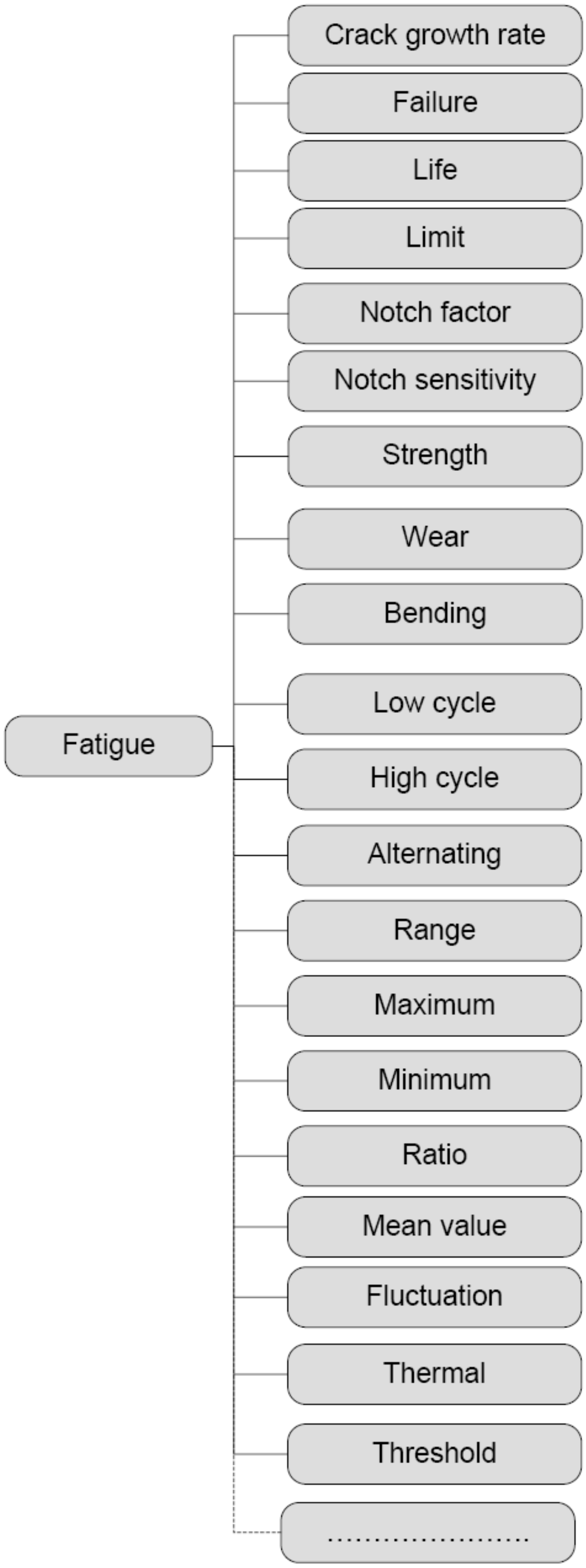


Figure 18 — Classification of fatigue behaviour

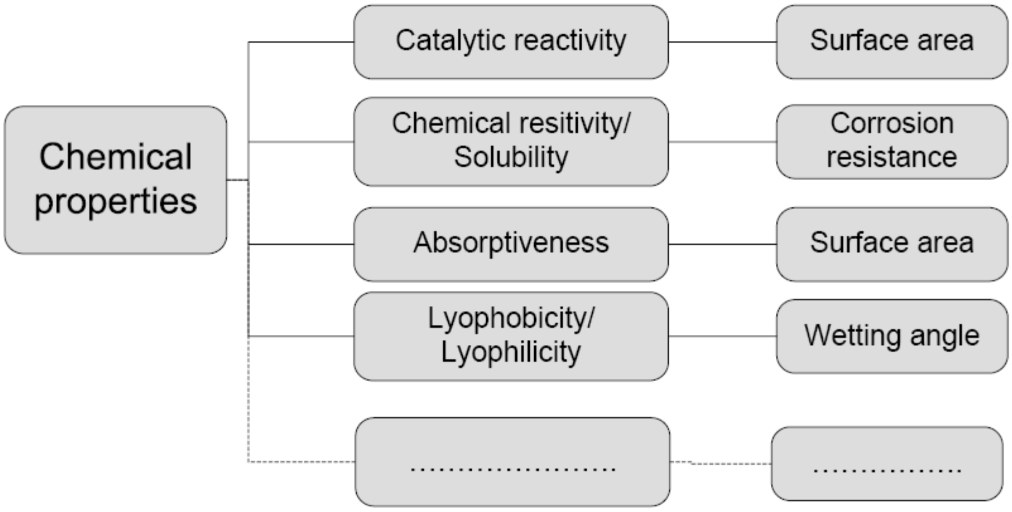


Figure 19 — Classification of chemical properties

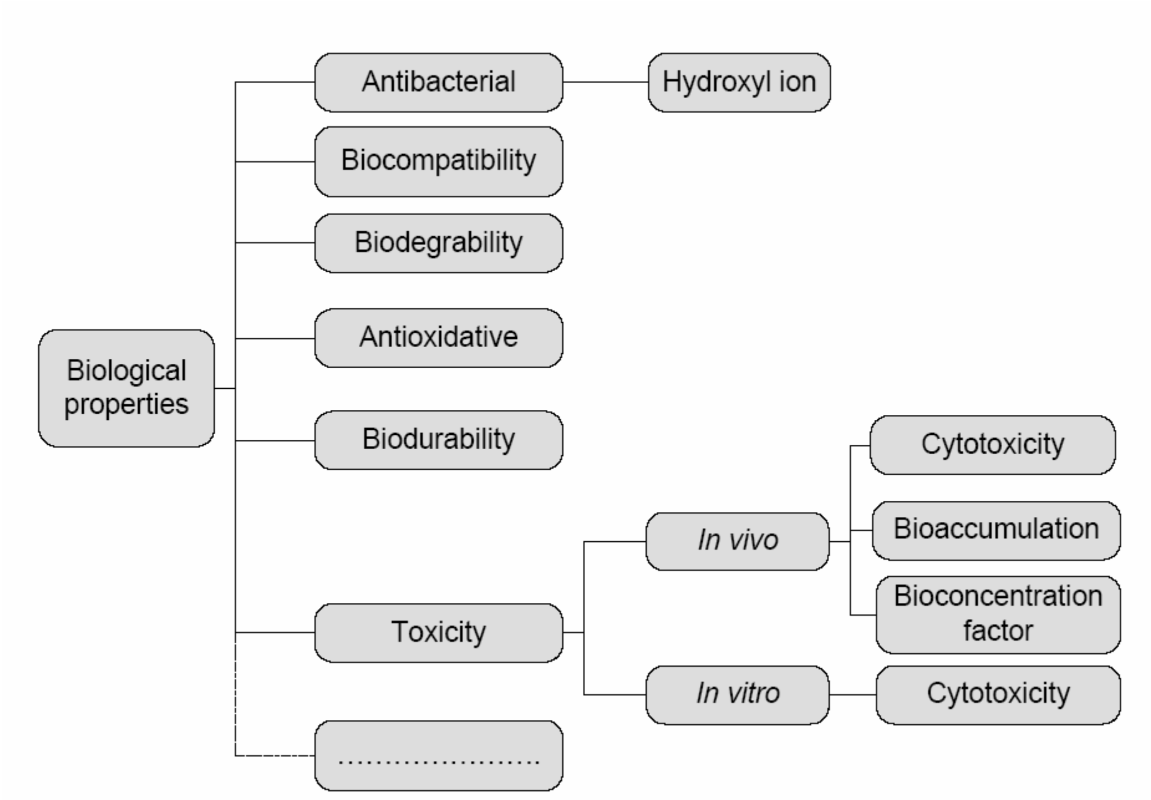


Figure 20 — Classification of biological properties

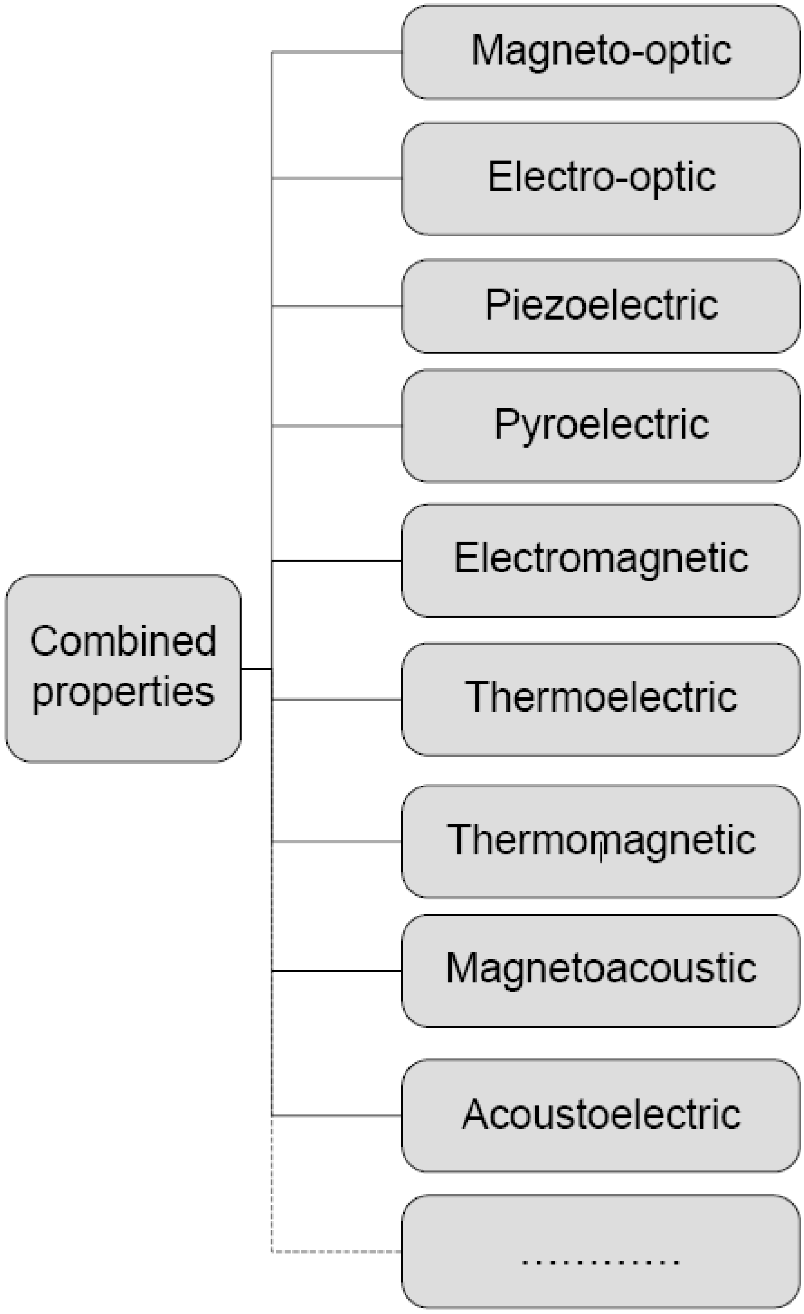


Figure 21 — Classification of combined properties

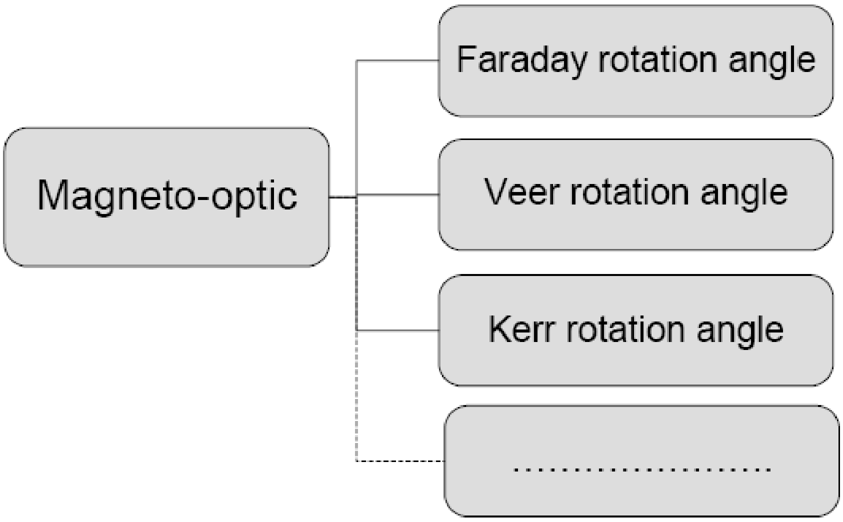


Figure 22 — Classification of magneto-optic behaviour

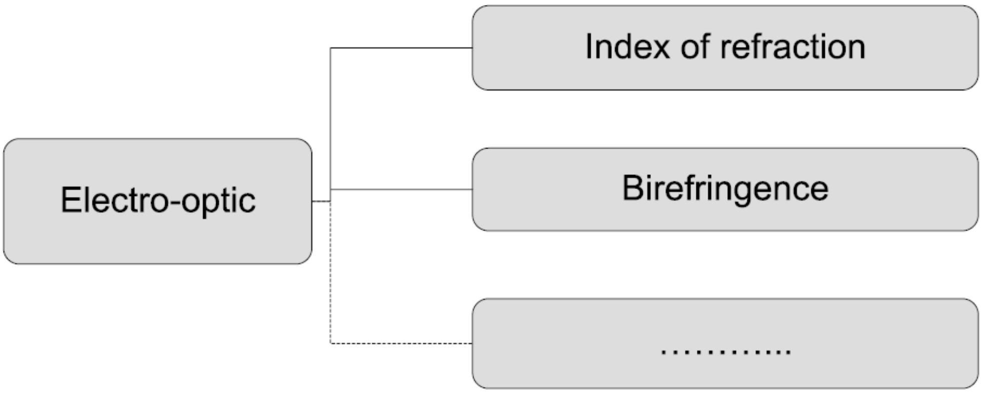


Figure 23 — Classification of electro-optic behaviour

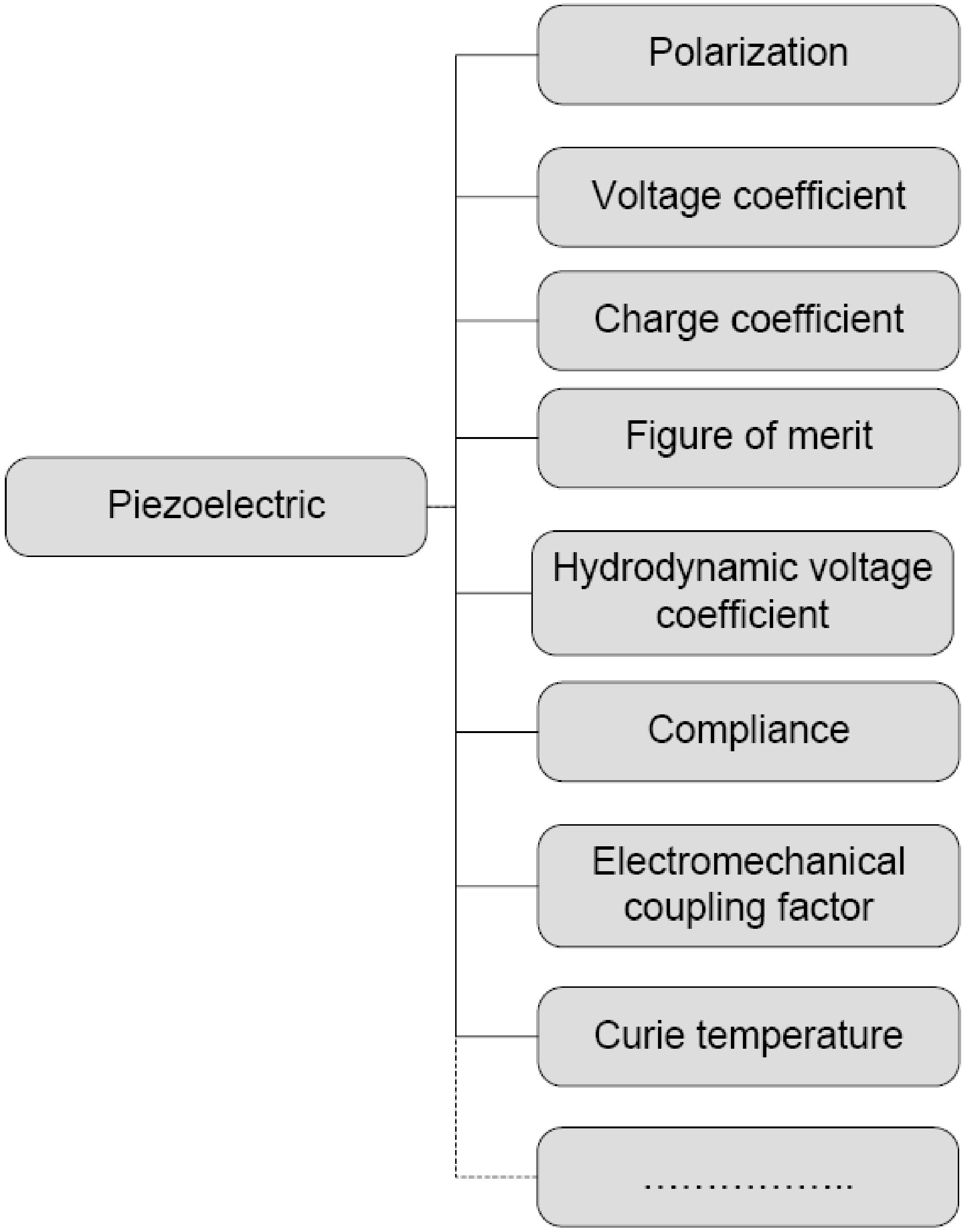


Figure 24 — Classification of piezoelectric behaviour

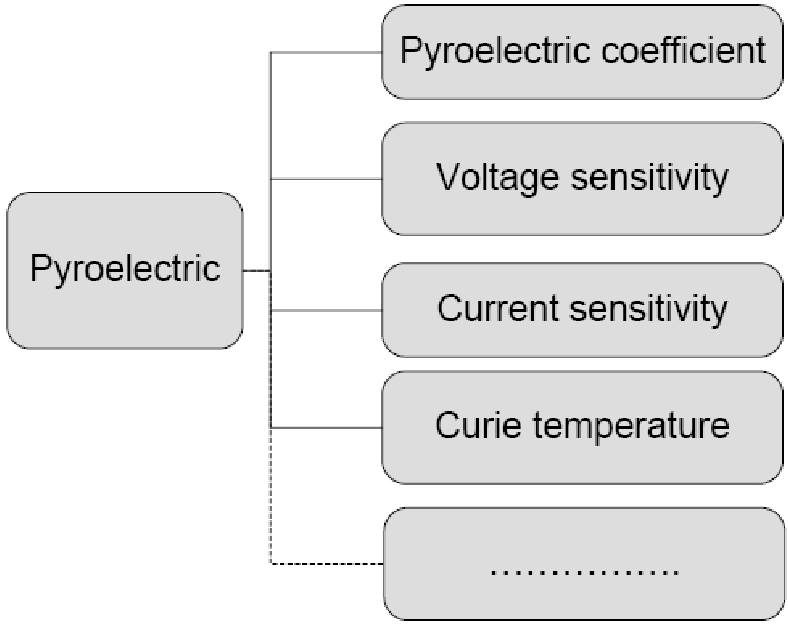


Figure 25 — Classification of pyroelectric behaviour

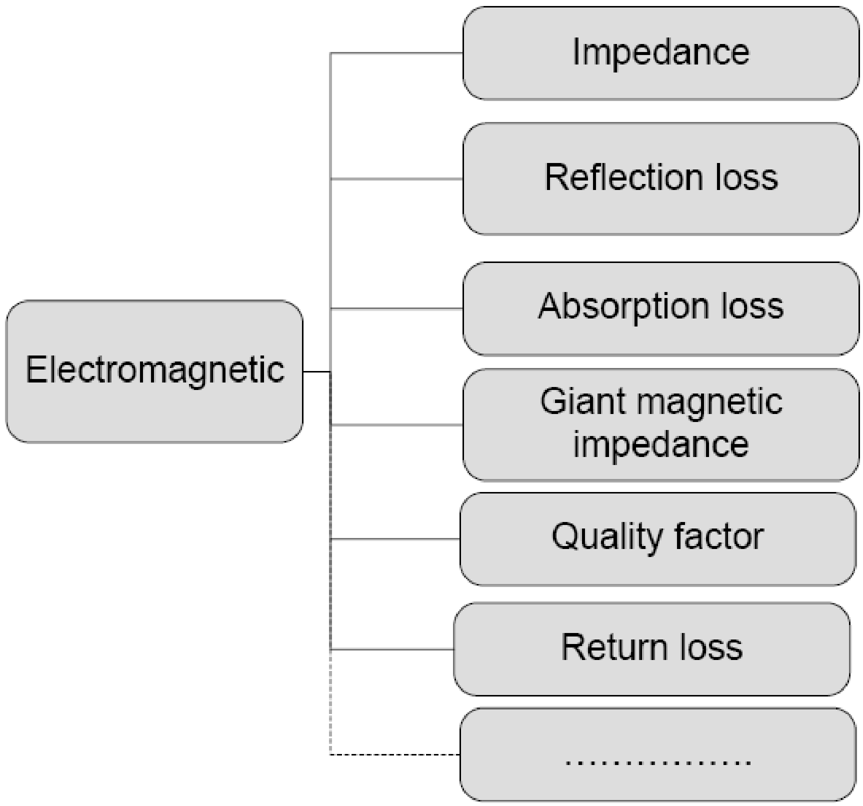


Figure 26 — Classification of electromagnetic behaviour

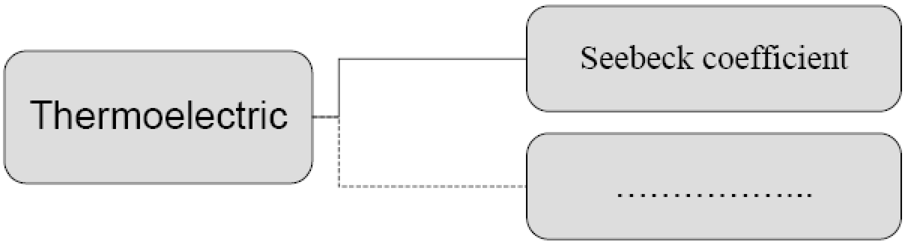


Figure 27 — Classification of thermoelectric behaviour

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