Investigación
Causality in Science

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Abstract

Causality is a fundamental notion in every field of science. Since the times of Aristotle, causal relationships have been a matter of study as a way to generate knowledge and provide for explanations. In this paper I review the notion of causality through different scientific areas such as physics, biology, engineering, etc. In the scientific area, causality is usually seen as a precise relation: the same cause provokes always the same effect. But in the everyday world, the links between cause and effect are frequently imprecise or imperfect in nature. Fuzzy logic offers an adequate framework for dealing with imperfect causality, so a few notions of fuzzy causality are introduced.

Keywords: Causality, Causal Relationship, Soft Computing, Deduction.

1. Causality in human cognition

Causality plays and has played an important role in human cognition, in particular in human decision-making, providing a basis for choosing an action which is likely to lead to a desired result. There are many works and theories about this theme. Philosophers, scientists, physics, mathematicians, computer scientist and many others have explored the field of causation starting with the ancient Greeks three thousand years ago.

The idea that causal knowledge is an essential feature of our understanding of the world is very old. In Metaphysics (*I, 1, 981 a 24-30*), Aristotle maintains that knowing is knowing attending to the causes:

"But yet we think that knowledge and understanding belong to art rather than to experience, and we suppose artists to be wiser than men of experience (which implies that wisdom depends on art in all cases rather on knowledge); and this because the former know the causes but the latter do not".

In daily life, causality is present in many situations. If someone fails to stop at a red light and there is a car accident, it can be said that the failure to stop was the cause of the accident. However, failing to stop at a red light does not guarantee that an accident will happen for sure [1]. Sometimes, true statements do not lead to a valid reasoning, as in J. Pearl's example [2]:

1. *"If the grass is wet, then it rained.*
2. *If we break this bottle, the grass will get wet.*
3. *Output → If we break this bottle, then it rained".*

So, to consider a statement as causal, it has to fulfil three properties which mean that the cause must precede the effect, cause and effect must be materially related, and whenever the cause happens, the effect must take place [3]:

1. Asymmetry: the cause always happens before the effect.
2. Linearity: any cause is followed by an effect.
3. Transitivity: if *A* causes *B* and *B* causes *C*, *A* causes *C*.

According to the way that causal statements are expressed and the type of relationship between the antecedent and the consequence, causality can be divided into the following types:

- Forward and backwards causality: forward causality is expressed in the form: "*What are the effects caused by a concrete event?*" and the inverse causality (or backwards), is expressed in the form "*What actions have been provoked by a certain event?*". In context, the forward causality is easier to deal with than the inverse causality, because, the action involved is usually known. In the inverse causality there can be multiple factors that have provoked an action, therefore it is much more complex to deal with and analyze.
- Direct and indirect causality: in '*A causes B*', *A* is a direct cause of *B*. If *A* causes *B* and *B* causes *C*, *A* is an indirect cause of *C*. Direct causality is linked to the linearity property and indirect causality is related with transitivity property.
- Token and type causality: in '*A causes B*', *A* and *B* are usually referred to singular events or tokens, as in *if John takes a trip, he will be happy*, or to

general events or type: *climbing stairs leads to fatigue*. Causal laws are performed with type statements.

- Positive and negative causality: a cause may have a positive influence on the effect: *low taxes favour the consumption*, or a negative one, *high taxes worsen consumption*.

- Plural and single causality: in '*A causes B*', *A* is a single cause of *B*. In *'A, B, and C cause E'*, *A*, *B*, and *C*, are plural causes of *E*.

2. Causality in Science

Causation plays a different role when analyzed from different fields. In legal ambiences it is a matter of conduct and result, while in science, such as physics it is the result of empirical experiments and evidence. This section enumerates the vision of causation through several fields.

- Science [4]: using the scientific method, scientists set up experiments to determine causality in the physical world. Elemental forces such as gravity, the strong and weak nuclear forces, and electromagnetism are known as the four fundamental forces which are the causes of all other events in the universe. However, the issue of to which degree a scientific experiment is replicable has been often raised and discussed. The fact that no experiment is entirely replicable questions some fundamental assumptions in science. In addition, many scientists in a variety of fields disagree that experiments are necessary to determine causality. For example, the link between *smoking* and *lung cancer* is considered proven by health agencies of the United States government, but experimental methods (for example, randomized controlled trials) were not used to establish that link.

- Physics [3]: in physics it is useful to interpret certain terms of a physical theory as causes and other terms as effects. Thus, in classical (Newtonian) mechanics a cause is represented by a force acting on a body, and an effect by the acceleration which follows as quantitatively explained by Newton's second law. For different physical theories the notions of cause and effect may be different. For instance, in Aristotelian physics the effect is not said to be acceleration but to be velocity (one must push a cart twice as hard in order to have its velocity doubled[1]). In the general theory of relativity, too, acceleration is not an effect (since it is not a generally relativistic vector); the general relativistic effects comparable to those of Newtonian mechanics are the deviations from geodesic motion

[1] Aristotle, Physics, Book VII, part 5, 249

in curved space-time [5]. Uncaused motion is also dependent on the theory: for Aristotle it is (absolute) rest, for Newton it is inertial motion (constant velocity with respect to an inertial frame of reference), in the general theory of relativity it is geodesic motion (to be compared with frictionless motion on the surface of a sphere at constant tangential velocity along a great circle). So what constitutes a "cause" and what constitutes an "effect" depends on the total system of explanations in which the causal sequence is embedded. For example, it is not accurate to say, *"the moon exerts a gravitational pull and so the tides rise"*. In Newtonian mechanics, gravity is a law expressing a constant observable relationship among masses, and the movement of the tides is an example of that relationship. There are no discrete events or "pulls" that can precede the rising of tides. Interpreting gravity causally is even more complicated in general relativity.

- Engineering [6]: a causal system is a system with output and internal states that depends only on the current and previous input values. A system that has some dependence on input values from the future (in addition to possible past or current input values) is named an acausal system, and a system that depends only on future input values is an anticausal system. There are many kinds to graphically represent causality in this field, for example the so called fishbone diagrams or cause and effect diagrams, commonly used for product design and quality defect prevention, to identify potential factors causing an overall effect.

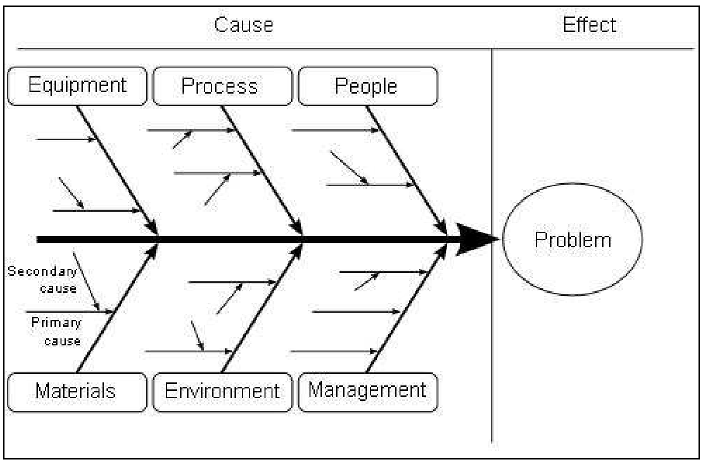

Figure 1: Representation of a fishbone diagram [6]

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- Biology and medicine [7]: Bradford Hill pointed that the following aspects of an association needed to be considered to distinguish causal from non-causal associations in the epidemiological situation:

    1) Strength: it refers to the numerical strength of the correlation, expressed as the relative risk to take a disease.

    2) Consistency: it refers to phenomena that have been observed in many places at many times by many different observers in different circumstances.

    3) Specificity: it means when the effect is limited to certain workers in specific situations and when there is no other association between the work and other situations of dying.

    4) Temporality: it has to do with the direction of causality. This aspect is particularly relevant when slowly progressing disease is concerned, as in the example "*Does the patient's diet cause the disease or does the disease alter the patient's diet?*".

    5) Biological gradient: it is also known as a dose-response relationship, when an increment of the supposed cause is associated with an increase in the response (or disease). For example, not only do smokers have a higher prevalence of lung cancer than non-smokers, but also heavy smokers have a higher prevalence than light smokers.

    6) Plausibility: it refers to the scientific credibility of the relationship. In the case of smoking, cigarette smoke is known to contain many established toxins, which makes it a plausible cause of cancer.

    7) Coherence: it is the idea that the possibility of the causal relationship should not conflict with what is known about the natural history and biology of the disease.

    8) Experimental: evidence has to be relevant. For example, if it is suspected that dust is causing the disease, then an experiment in which dust filters are installed would be appropriate and, if successful, would confirm the theory that dust was a causal factor in the incidence of the disease.

    9) Analogy: it is when the reasoning comes from similar phenomena.

- Humanities, law[2]: in the legal field, causation is the *"causal relationship between conduct and result"*. Causation of an event by itself is not sufficient to create legal liability, though establishing causation is required to establish legal liability. Usually it involves two stages:

  1. The first stage involves establishing '*factual*' causation. For example, *Did the defendant act in the accuser's loss?*.

  2. The second stage involves establishing '*legal*' causation. For example, *Is this the sort of situation in which, despite the outcome of the factual investigation, the defendant might be released from liability, or impose liability?*

3. A probabilistic view of causation

Scientific laws tie always together cause and effect. Therefore, the causal principle must guarantee without exceptions *B* whenever *A* happens. In colloquial language, *'Every effect has its cause which is always the same'* or *'The same causes lead to the same effects'*. But this is not always true. Both in scientific and literary texts is possible to find laws or principles that link the cause to the effect in a partial or imperfect way as in the sentence *If the potential is carefully adjusted, and has a false vacuum local minimum, it is possible to obtain a solution that is non - singular over the whole four – sphere* (S. Hawking, Quantum Cosmology). These laws have the form of causative or conditional sentences. Causal relationships do not always denote precise and stable links between cause and effect but, in many cases, they refer to partial or approximate ones.

In the scientific area, quantum mechanics was the first field to show the imperfect character of causality. The laws of quantum physics suggest causal connections that are not absolutely true, but only probable. The Heisenberg uncertainty principle radically changed the criteria of classical causality: in general, in a quantum universe, the same cause does not always lead to the same effect, but a variety of possible effects, each of them with a certain probability. Quantum mechanics introduces the probability on the principle of causality.

The probabilistic view of causality has some differential characteristics:

1. While the laws of classical mechanics refer to universes of discourse with sharp and distinguishable elements, the laws of quantum mechanics speak about collections from which their cardinality can be found, but

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[2] Standford Encyclopedia of Philosophy http://plato.stanford.edu/

not always their elements. Quantum sets are *posets*: an element belongs or not to the set, but it is not always possible to identify whether the element of the collection is the same as others previously identified.

2. Linking cause and effect involves determining the set of factors that compose the cause [8]. In the quantum world, some of these factors are measurable and others are not; and therefore never completely determined. Causation emerges from the relationship between measurable individual parameters. Probability is related with the distribution of the residual parameters. If an event can be described by a finite list of parameters, it is possible to predict its evolution with a probability that tends towards 1 as more parameters are taken into account.

A probabilistic view of causation is convenient for correctly interpreting some physical laws, such as those related to the kinetic theory of gases, because the number of molecules to consider is in the order of the Avogadro's constant (6×10^{23}) and, thus, impossible to manage in a deterministic way. Therefore, it is needed a probabilistic approach.

The laws governing quantum causality are stochastic and indeterminate -as it is not possible to know all the parameters involved in the nature of a fact-, but precise -as once performed the experiment, a value is obtained-. Quantum laws are a mixture of reason and experimentation: experimentation puts limits on what it is possible to know; reason determines the value of what is known. But there are fields in which causation is not, generally speaking, a crisp relation, but ill defined and fuzzy.

4. Fuzzy Causality

Causality is many times an imprecise and imperfect relationship between two entities, cause and effect. For this reason, Zadeh [9] remarks that does not exist a definition of causality within the conceptual structure of classical logic or probability theory, able to provide a reasonable answer to the following points:

1. The definition has to be general, not restricted to a narrow class of systems or phenomena.
2. This definition has to be precise and unambiguous, in order to be used as basis for logical reasoning or computation.
3. Given two causally connected events, *A* and *B*, this definition has to be able to answer the questions: a) *Did or does or will A cause B or vice-versa?*, and b) *if there is a causal link between A and B, what is the*

strength?.

Zadeh also points out three sources of difficulty in defining or establishing causality. The first one is chaining, that is a temporal chain of events, $A_1,A_2,A_3….A_n$, which ends on A_n. The difficulty here relies on determining to what degree (if any) A_i($i=1,….,n-1$) causes A_n. In [1], it is introduced some examples about the problems that causal chains present:

- *Simultaneous Plant Death*: "*my rose bushes and my neighbour's rose bushes both die. Did the death of one cause the other to die? (Probably not, although the deaths are associated)*".
- *Drought*: "*there has been a drought. My rose bushes and my neighbour's rose bushes both die. Did the drought cause both rose bushes to die? (Most likely)*".
- *Traffic*: "*a friend of mine calls me up on the telephone and asks me to drive over and visit him. While driving over, I ignore a stop sign and drive through an intersection. Another driver hits me, and I die. Who caused my death?*"
- *Poisson*: "*Fred and Ted both want Jack death. Fred poisons Jack's soup, and Ted poisons his coffee. Each act increases Jack's chances of dying. Jack eats the soup, and feeling rather unwell leaves the coffee, and dies later. Ted's act raised the chance of Jack's death but was not cause of it*".

Another problem that Zadeh remarks is the confluence or conjunction. In this case it is presented a confluence of events $A_1,A_2,A_3….A_n$ and a resultant event *B*. the problem here is to calculate to what degree each event separately caused the final event *B*. To demonstrate this problem, Zadeh proposes two examples:

- *A raincoat manufacturer would like to increase his sales. To this end, he increases the advertising budget by 20%. Six months later, sales went up 10%. Was the increase on sales caused by the increase in the advertising budget? If so, to what degree?*
- *Business news announces that the stock market had a sharp drop. Analysts cite as primary reasons for the drop a 2% increase in unemployment, and 3 dollar-a-barrel increase in the price of oil. To what degrees did the unemployment and the price of oil caused the sharp drop?*

The third problem is covariability, seen as a statistical association. In this case, A and B are variables, and there appears to be a deterministic or statistical covariability between A and B. The problem is establishing if this covariability is a causal relation. Moreover, when is a relation a causal relation? Differentiation between covariability and causality presents a difficult problem, especially in the context of data mining. Causality is referred to demonstrated and established facts; given a cause, an effect happens, but covariability is related more to coincidence and undemonstrated set of facts, despite it is noticeable that if something is changed (the cause), the output is affected (effect). For example, it is generally assumed that aging causes a loss in acuity of hearing. However, recent studies have shown that the loss in acuity is caused by prolonged exposure to high levels of sound and not by aging per se. Or another example, I fell at home and broke my right leg and my left arm. Is there a causal connection between breaking my right leg and left arm?

Another author that considers causality in terms of fuzzy logic is Kosko [10]. He conceives fuzzy causation as a correlation between positive and negative occurrences of cause-effect pairs. Thus, to say that *alcohol is the main cause of road accidents* is, in his view, equivalent to say -in conditional terms-, that *drinking causes traffic accidents and not drinking prevents such accidents*; that is, A causes B is $(A \rightarrow B) \wedge (\neg A \rightarrow \neg B)$, which is $A \leftrightarrow B$. In other words, there is a correlation between *drinking* / *not drinking* and *increase* / *decrease* of traffic accidents. Causality is determined not only by positive correlations, but also by negative ones.

To deal with these problems, it is needed some tools able to handle imprecision and uncertainty. *Soft-Computing* methods may be able to provide the approximation tools needed.

The concept of *Soft-Computing*, which was introduced by Zadeh, serves to exploit the tolerance for imprecision and uncertainty, to achieve tractability robustness and low cost solutions by means of computing methodologies. In his own words, "*Basically, Soft-Computing is not a homogeneous body of concepts and techniques. Rather, it is a partnership of distinct methods that in one way or another conform to its guiding principle. At this juncture, the dominant aim of Soft-Computing is to exploit the tolerance for imprecision and uncertainty to achieve tractability, robustness and low solutions cost. The principal constituents of Soft-Computing are fuzzy logic, neurocomputing, and probabilistic reasoning, with the latter subsuming genetic algorithms, belief networks, chaotic systems, and parts of learning theory. In the partnership of fuzzy logic, neurocomputing, and probabilistic reasoning, fuzzy logic is mainly concerned with imprecision and approximate reasoning; neurocomputing with learning and curve-fitting; and probabilistic reasoning with uncertainty and belief propagation*". So, *Soft-Computing* is defined by means of different concepts and techniques to overcome the difficulties of real problems which happen in an imprecise world, uncertain and difficult to categorize.

To consider causality from a computational point of view, imprecise causal models are needed, so that *Soft-Computing* techniques need be applied. One of the main problems in this scope is how to computationally recognize and represent causal relationships. Another problem, once recognized this causal entailment between two concepts, is establishing the strength of this union. This could be a research area for many fields in the future.

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