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Fuzzy-defined entities: A key concept to strengthen forensic science foundations?

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ABSTRACT

According to the Sydney Declaration, "Forensic science is [… an] endeavour to study traces […] through their detection, recognition, recovery, examination and interpretation to understand anomalous events of public interest (e.g., crimes, security incidents)." This science is focused on establishing the nature and relationships among entities related to events having a potential legal impact. Entities can be (groups of) persons, objects, activities and their corresponding sources, events and traces. Although uniqueness of an entity has been traditionally accepted as a principle of forensic science, this paper argues and illustrates that such uniqueness is illusory: Not only can an entity evolve spatially and temporally, but at any specific instant, it *differs from itself* according to the level of precision at which it is considered. Its characteristics vary based on when, how and by whom it is perceived. We introduce the concept of fuzzy entities - defined to formally include some essential uncertainty or imprecision. The essential impreciseness and subjectivity of an entity gives a new perspective that allows us to revisit Kirk's principle of individuality and to propose to replace it with a new principle of *fuzzy unicity*. We believe that this new perspective has the potential to strengthen forensic science foundations and bring closer its disciplines, which is an important step towards a harmonized forensic science.

1. Introduction

Forensic science is often seen as a patchwork of multiple scientific disciplines. The Sydney Declaration begins with the following observation made by Kirk: "With all the progress that has been made in this field, and on a wide front, careful examination shows that for the most part, progress has been technical rather than fundamental, practical rather than theoretical, transient rather than permanent" [17]. The Sydney Declaration states that "how forensic science is characterized or defined and whether there are sufficient common ground principles to develop it into a specific discipline are at the base of the current reflection", then, further, "However, unlike for more established disciplines, a shared understanding and broad acceptance of the essence of forensic science, and its objectives, purpose and fundamental principles are still missing" [23].

We share these observations and are convinced that there is a need for common fundamental definitions and concepts to be shared across all forensic science disciplines in order to strengthen ties between them and to reach an overarching forensic science.

Forensic science is at the junction, amongst other, of natural sciences like physics, chemistry, or computer science as well as human sciences like psychology, sociology, or anthropology. In order to harmonize domains in forensic science, it is essential to define fundamental concepts in a common frame of reference across disciplines. Our reflection starts with the observation that these disciplines rely on a few fundamental concepts like (groups of) persons, objects, activities and their corresponding sources, events as well as their traces.

We deem that all these fundamental concepts rely on the even more fundamental concept of *entity*. Indeed, for example, objects are entities. The source of an activity is an entity. Events considered in forensic science are originated by entities which are not necessarily a person. A trace is an entity too. Moreover, identities are attributed to entities [1]. As the entity appears to be a core concept in forensic science, a sound definition for this term is of utmost importance.

In addition, entities are essential to communication; they are mostly what we communicate about. In forensic science, entities are used to

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communicate forensic findings and results. For a communication to be possible, each participant must be able to anchor its subjective perceptions and understandings on concepts mutually shared between communicating parties.

The preeminence of similar concepts in the mind of emitters and recipients of a piece of information allows communication through similar representations of the content of the information in each one's mind; it is the inter-subjectivity. These concepts are essentially those learned as individuals, through life experience, either directly or taught by peers. This learning process is related to the culture as described by Damasio [5]: A strategy developed by living organisms to help them stay alive through cooperation.

In his semiotics, Peirce formalizes the human conception of its environment, reasoning (second semiotics), and communication (first semiotics) building on the triadic concept of *sign*: What is directly perceptible (*representamen)*, the subjective conception of the perceived representamen (*interpretant*), and the actual *object* which is referred to[4]; see e.g. [6,7] and [20]. The subjectivity of entity perception and conception is addressed in Peirce's semiotics.

The aim of this paper is not to delve further into communication, but to focus on the concept of entity itself. We will discuss its subjectivity, its existence and what should be taken into consideration when defining it.

Kirk's principle of individuality (1963), a famous attempt to express a fundamental principle in forensic science has been highly discussed in the literature (e.g., [3,4]. According to Kirk, since each entity is unique in the universe, it has an individuality. In this article, we will challenge the very concept of *uniqueness*. We will propose to replace Kirk's principle of individuality by a new principle addressing some essential limitations of an entity's strict uniqueness.

Giving a precise definition of an entity appears quite difficult, probably because of the wide use of this concept and its apparent universality.[5] It is at the very root of relevant ontologies like [12],[6] [13] or CASE/UCO[7] and is pre-eminent to any attribution of relations between "things" or of qualifiers to "something" (e.g. an identity [1]). In other words, it is a prerequisite to the conception of the scientific models themselves which support inferences about the past or the future, about events that were not observed (typically in forensic science, paleontology, or cosmology) or have not happened yet.

The following sections will emphasize ground limitations around the concept of entity, explicit expectations for entities and propose to distinguish two meanings for the existence of an entity. Then the general concept of *fuzzy definition* will be introduced to take into account previous considerations when defining specific entities. Last but not least, we will illustrate possible impacts of fuzzy-defined entities on forensic science.

2. Ground limitations of the concept of entity

We think that the concept of entity has intrinsic and extrinsic limitations. Intrinsic limitations, on one hand, emerge due to the order of magnitude at which an entity is considered. Furthermore, some orders of magnitude are more relevant than others and depend on the expectations and the context of the observation. Extrinsic limitations, on the other hand, are due to human perception and mental conception, which are sense based and may be considered at different levels of abstractions. Since both kind of limitations may vary mentally or over space and time, it is essential to formally integrate the variations ranges in which a given entity is considered. We will make use of the concept of fuzzy definition of an entity in order to explicitly introduce these variations.

First, we show that a definition of an entity can be done at best for a given level of precision.[8] Moreover, some levels of precision are pertinent whilst others seem irrelevant. To illustrate intrinsic limitations, we consider the famous example of a coastline – the entity delimiting sea and land.

At an altitude of 10 km and with normal eyes, we see a clear coastline: The limit between sea and land. The corresponding level of precision is at the order of a few meters.

At a height of 10 m however, the distinction between sea and land is less clear. We can distinguish waves. The limit between water and sand is ever changing with some regularity. At a given frozen time (for example on a picture), we can still distinguish water and sand with a level of precision at the order of a few centimeters. If measured, this partial coastline seems longer than the corresponding section observed from a height of 10 km. This illustrates the fact that the length of a coastline is not absolute, it is a mental simplification which highly depends on the level of precision. To want to determine the exact length of a coastline is doomed to failure; this value cannot exist. This was already pointed out in the coastline paradox described by Richardson [22] and later by Mandelbrot [19].

At a height of 1 mm, assuming we could follow the moving zone where waves are dying on the sand, we could not distinguish a precise limit at all, a part of the sand being continuously wet but not really in the sea. The coastline is not a simple line anymore, it is at best a *thick* fuzzy line, a kind of evanescent strip.

Eventually, at a height of 1 nm, if the word height still had any meaning here, it would make no sense at all to speak about a coastline since this is the scale of a water molecule.

For the coastline, depending on the question to be solved, some precision levels are more relevant than others.

We can generalize this example to any object, e.g., to a spoon. Considering it at a distance of 1 km, 1 m or of 1 Å requires a different level of precision to be chosen and gives a different sense of "reality". At a coarse level of precision (say, 50 cm or more) the spoon is not even perceptible. A pertinent level of precision needs to be at most in the order of its width, i.e., about a few millimeters. What belongs to the spoon and what does not might seem clear up to a precision level of a micron. This is not the case anymore at the level of the atoms: It might be difficult to decide if a specific electron belongs to the spoon or to its environment. Again, the limit is not a perfect surface with no thickness. It is at best a thick and fuzzy volume delimitation.

These examples motivate us to conclude that, due to these intrinsic limitations, any sound definition of an entity should explicitly include the level of precision at which it is considered. Therefore, in general, an entity is essentially not the same at different levels of precision, its uniqueness does not make sense anymore. We consider that the "uniqueness of an entity in the universe" as mentioned in Kirk's principle of individuality (1963) is nothing but a simplifying illusion.

Second, it is important to acknowledge that human conception of one's environment is based on the use of human sensory perception and layers of abstraction. Perceptible signals are either directly perceived through our senses (e.g., visible light emitted or reflected by an object, haptic sensations when touching this object, sound perceived from this object or possibly smell or taste of this object), or using instruments that convert original signals into a form that can be directly perceived (e.g., infra-red light transformed into a measure or visible light).

[4] This also relates to Hume's concepts of impression and ideas in *Treatise of Human Nature* (see e.g. [10]).

[5] It is often imprecisely defined, using words like "something" or "anything". For example, the Oxford Learner's Dictionaries definition of an entity is "something that exists separately from other things and has its own identity, https://www.oxfordlearnersdictionaries.com/definition/english/entity?q=entity (accessed 25 October 2023).

[6] See also Basic Formal Ontology available at https://basic-formal-ontology.org/ (accessed 25 October 2023).

[7] See https://caseontology.org (accessed 25 October 2023).

[8] For now, this term is to be understood here as an order of magnitude. A formal definition of the *level of precision* is given in the "Definitions: Level of precision and indistinguishability" box below.

Signals coming from each sensory channel are processed to create a live representation of what we perceive, using the human brain synchrony of senses mechanism [15]. Our brain tends to classify our sensory perceptions of our environment in categories. The mental mechanism of categorization is described by cognitive psychology (see for example [8]. The human brain categorization process is a threshold-based mechanism which can produce different levels of approximations (see for example [16]; [21]; [18]; [25].

This leads to mental, subjective representations of an entity with some stability over time. We use entities to model the world around us. Entities do not exist in the exact same way outside of our brain and as representations within our brain. This is captured by the concept of sign as a triad proposed by Peirce [20]. Since these mental representations are filtered out by a threshold-based process, perceived entities cannot be fully accurate. This is referred to as extrinsic limitations.

3. Existence of an entity

We deem that entity approximations can easily stay unnoticed because the mechanism of simplification and categorization which produce entities is the natural and intuitive way to model the environment. So we are of the opinion that there is a simplification of reality that is superimposed in a human mind to the "external reality" [2]. As human beings, we often believe that an entity exists as a whole unit, locally constant in space and time, outside of our mind. This echoes the psychological and epistemological concept of constructivism[9] for the mental representation of an entity and the philosophical concept of perdurantism for the existence of an entity over time.

The above considerations also impact the concept of existence. Let us consider a sandpile. It can be interacted with (divided, transported, stolen, etc.). But when its grains are retrieved, one after the other, it loses its meaning after a certain, not precisely defined, number of remaining grains are removed. What is the meaning of the existence of the sandpile? When does it cease to exist?

Now we consider a glass that falls and breaks on the ground. Does the glass still "exist" after it broke? Breaking the glass does not really impact the existence of its originally constituting atoms. Of course, this example can easily be generalized to any object constituted by atoms. We could push this mental experiment further to atoms being constituted by quarks and electrons and so on, but our goal is to demonstrate that macro entities are purely subjective, not to delve into physical models describing the constitution of the matter.

More generally, we want to point out that divided matter parts, as for the glass pieces after it broke, are themselves smaller entities. These smaller entities, like the glass itself, are mental representations at different levels of precision and abstraction. It is implicit when Inman and Rudin [11] introduce the principle that "matter must divide before it can be transferred".

We think that the concept of existence is not as obvious as it seems and should be considered cautiously. Nonetheless we acknowledge the convenience of its role played in the process of communicating about "things" that are perceived and mentally represented, even though such a representation does not imply the existence of what is represented.

As already mentioned, entities do not exist in the exact same way outside of our brain and as representations within our brain. We would like to distinguish between two kinds of existence in order to emphasize the difference between the representation of something and this "thing" itself [2]. The first kind of existence is sometimes referred to as the "real one"; what supposedly "is", without anybody interacting with it or what might still exist even if nobody is observing it. We will not argue about the reality of it and think that this belongs to another philosophical debate. The second kind of existence is the "perceived one" (Peirce's *interpretant* of a representamen, i.e. a thought that points to an object) which is by nature subjective. This existence through perception allows to build "common sense" as well as scientific thinking and reasoning. It is populated with representations that each person makes of their environment in their brain.

[9] For the psychological constructivism, see for example [9] who refers to numerous publications from Jean Piaget on the topic.

4. Expectations for entities

Another consideration is related to the expectations for the concept of entity. We deem that entities should include some persistence, continuity or similarity over space and time. It is important for a human being to be able to recognize and conceive a perceived object, from a certain distance, at a pertinent level of precision and during some "practical" interval of time. A given ocean wave "exists" during a few seconds/minutes, rarely more than an hour (e.g., a tsunami) and it makes no sense to consider a repetition of a coin toss over a billion years since the coin will never keep its shape over this duration. These expectations are needed to model the environment around us in a sufficiently stable way, then to apply reasoning on this model, to give meaning to entities and to share conceptions (through communication).

It is well known that persistence, continuity, and similarity are not straightforward. Is an adult the same entity as the corresponding child in the past? This is famously illustrated by the philosophical thought experiment of the ship of Theseus; it was repaired so many times that each piece constituting it had been replaced at least once. Was it still *the* ship of Theseus or just a ship belonging to Theseus? Actually, *the* ship of Theseus might be considered as the abstract class of considered-to-be-equivalent "concrete" ship instances over time. However, this kind of similarity does not define a strict mathematical equivalence relation; it is closer to the mathematical concept of tolerance relation which is weaker (not always transitive). Hence the dilemma. This example deals with the philosophical concept of ipseity. Pushed to its limit, other questions arise from this dilemma: Is an object the same at two different instants, even if it has lost an electron in the meantime? Does it even make sense to consider a specific electron in quantum physics as the same particle over time? With those examples and considerations, we want to underline once again that, as for a "Trace" [14], it does not make sense to define an entity with infinite precision.

The concepts of level of precision and indistinguishability can be defined formally:

Definitions: Level of precision and indistinguishability

Let denote U(t) the set of all possible parts of the universe at time t, and U, the union of all U(t). A distinction function D is any symmetric function defined from U x U to {0; 1}. The level of precision corresponding to a given distinction function D is defined as follows:

$$D(u_1(t_1); u_2(t_2)) = 1$$

if and only if $u_1(t_1)$ and $u_2(t_2)$ can be distinguished at this level of precision.

We say that parts $u_1(t_1)$ and $u_2(t_2)$ are indistinguishable at this level of precision if

$$D(u_1(t_1); u_2(t_2)) = 0$$

Of course, not all distinction functions make sense. However, distinction functions that reflect an order of magnitude allow to formally define relevant levels of precision.

It is noteworthy to emphasize the importance of the time in the above definitions. For example, it is possible that two realizations of the ship of Thesus, for example u_1 at time t_1 and u_2 at time t_2 are indistinguishable at a given level of precision even though they are distinct.

It is also important to point out that a distinction function is not always transitive.

5. Fuzzy definitions

The coastline, the spoon, the glass, or the ship of Theseus in the here above examples cannot be precisely and objectively defined. Usually, such entities are implicitly defined. They are abstractions, approximately defined at practical spatial and temporal levels of precision by a human mind to grasp its environment.

We need to introduce the concept of *fuzzy* definition that allows us to define entities more formally.[10] A *fuzzy definition* is a definition that includes some essential uncertainty or imprecision.

Let's consider, as an example, a surface delimited at a given level of precision, at a fixed time. In order to fuzzy-define it, we can associate values between 0 and 1 – weightings (of being part of the surface) – to each subset of indistinguishable (at this level of precision) points of a neighborhood[11] of this surface. A weighting of 0 means that the subset of indistinguishable points is not part of the surface, a weighting of 1 means that it is. An in-between weighting means that the subset of indistinguishable points is located within the fuzzy delimitation of the surface.

This method allows us to subjectively define the surface as weightings can be freely chosen. Weightings do not necessarily vary in a regular way.[12] Moreover, subjective densities of probabilities, for example, might be used to define subjective weightings. When time goes on, weightings can evolve.

As another example, to define the coastline at a given level of precision at a fixed time, we could associate to each subset of indistinguishable parts (smaller than the level of precision) of the coast a subjective probability estimating the "average belonging to the sea". With this approach, the coastline is the reunion of all subsets with a subjective probability greater than 0 and smaller than 1.

The fuzzy definition of a specific entity at a given level of precision (in space and time) should take into account and reflect both the intrinsic and extrinsic limitations that we discussed above.

Previous sections show the necessity to consider subjective fuzzy-defined entities (fuzzy entities) rather than objective infinitely precise ones to formally define the fundamental concept of entity. There are numerous approaches to fuzzy define an entity in a sound way.

For example, we can rely on a distinction function. What is distinguishable or not depends on perceptible signals (either directly perceptible through our senses or using instruments that convert original signals into a form that can be directly perceived). A well-chosen distinction function D can locally model what is distinguishable at a certain order of magnitude, i.e. what leads or not to a perceptible difference.

We propose the following definition for the concept of *fuzzy entity* with respect to a given distinction function.

Definition: Fuzzy entity

Let us define the concept of *completely indistinguishable* set: A set of parts of the universe is *completely indistinguishable* with respect to the distinction function D if, for any parts $u_1(t_1)$ and $u_2(t_2)$ in this set, $u_1(t_1)$ and $u_2(t_2)$ are indistinguishable, i.e. D $(u_1(t_1); u_2(t_2)) = 0$. To each completely indistinguishable set with respect to the distinction function D, we associate a (possibly subjective) value between 0 and 1: Weightings of being part of the entity. A weighting of 0 means that the completely indistinguishable set is not part of the entity, a weighting of 1 means that it is. An in-between weighting means that the set is located within the fuzzy delimitation of the entity.

The aim of this paper is to open the discussion about fuzzy entities. Other robust fuzzy definitions of an entity can be explored.

In a similar way, events, activities, sources or even traces are often intuitively defined in forensic science. We consider that they should be fuzzy-defined too. Actually, the definition of a Trace in [14] already uses fuzzy definitions without naming it.

Understanding the implication of such approximations on the foundations and the development of forensic science seems important. We believe that integrating such reflection in fundamental definitions will lead to more transparency in reasoning and to the development of more faithful and relevant models by highlighting their intrinsic imprecision, their domain of application as well as some of their potential limits.

6. Possible impact on forensic science

Even at any specific instant, an entity *differs from itself* according to the level of precision at which it is considered. Moreover, at a fixed level of precision, an entity varies as time goes by. This is to be compared to the *dynamical object* defined by Peirce [20] which must be distinguished from the *immediate object*. Since in general an entity differs from itself in time and space, strict unicity is a simplifying illusion. This impacts the concept of uniqueness as expressed in Kirk's principle of individuality [17]. Unicity can only make sense up to a certain level of precision. The concept of fuzzy unicity addresses this issue.

We can define the concept of *fuzzy unicity* as follows:

Definition: Fuzzy unicity

For a set of fuzzy-defined entities and with respect to a precision function D, fuzzy unicity means that all pairs of fuzzy-defined entities in this set are indistinguishable. In particular, in a fuzzy unique set, entities do not differ from themselves with respect to the underlying precision function.

We propose to replace Kirk's principle of individuality (1963) by this new principle of *fuzzy unicity*.

Fuzzy unicity principle:

Fuzzy unicity – with respect to an underlying distinction function – implies that different fuzzy entities can be indistinguishable from each other, at the level of precision related to the distinction function, creating an illusion of individuality.

More generally, using adequate levels of precision, it is even possible to "fuzzy-unify" categories of traces that otherwise are considered as distinct. Distinction is primarily due to the level of abstraction they are considered at, i.e. the level at which pertinent information is mentally modeled.[13] We suggest to consider the *whole* Trace as defined in [14] instead of a few of its typical facets. Choosing an adequate level of precision might reveal other facets of the Traces that annihilate traditional simplifying distinctions.

As an example, we consider the distinction made between physical traces and digital traces. The Sydney Declaration states that "the traceability of human activities is rapidly changing in our digitalized (i.e., combined physical and digital) environment". It also mentions that "trace interpretation helps decipher the mechanisms underlying many forms of crimes and harmful events taking place in both a physical environment and digital, computerized infrastructures" [23].

Digital traces are called *digital* because they are constituted by binary bits at the level of abstraction they are typically considered. However, digital traces have physical facets too. At some levels of precision, the constituting bits are stored, for example, in the magnetic fields situated on a hard disc drive or the electrical voltages at the gate of transistors in the flash memory of a solid-state drive. It is worth noticing that such a facet of a digital trace is analogical. The use of an analog-to-digital converter (ADC) transforms those analog values into abstract discrete values (bits) using a threshold function.

At a higher level of abstraction, bits (and the corresponding digital facets of the Trace) tend to be easily replicable: These bits can be read very quickly, copied, and transferred; the information associated with them can be transcribed back into an electromagnetic signal which can be routed over a cable or emitted as a radio wave via an antenna.

Each process of replication of the information – e.g., each time the bits are read – can be considered as an enlargement of the physical trace to be taken into account. Furthermore, since those replications are travelling over physical mediums, their physical substrates are evolving over time. Since those signals are travelling at extremely high speed,

[10] Based on the concept of fuzzy sets as introduced by Zadeh [26].

[11] Neighborhood is to be understood as a topological neighborhood in mathematics for a relevant topology of the universe.

[12] Moreover, nothing proves that our universe is continuous in the common sense.

[13] We would like to emphasize the difference between a level of abstraction and a level of precision. The level of abstraction refers to the information level at which an entity is considered; a level of precision is related to the order of magnitude at which a perceived entity is considered.

near the speed of light, the spatial localization of the physical-digital trace may be huge – for example in the case of traces stored in a cloud computing infrastructure – even if considered only during a very short period.

Another example is a dump of the volatile memory (RAM) of a computer, which can be seen as the preservation of the physical state of various voltages at the gates of the transistors constituting this memory.

Thus, we suggest recognizing, at least formally, that digital traces are part of physical traces (but not the opposite). The main distinction between both categories might arise in terms of pertinent levels of abstraction at which they are typically considered and that create the illusion of a fundamental difference. Considering a digital trace as being different from a physical trace is only for convenience. The distinction can be helpful as far as it does not lead to misinterpretation.

There is certainly an optimal level of precision for various categories of traces; it is not worth trying to observe traces at an ever-finer level of precision. Moreover, choosing appropriate levels of precisions may also foster bridges between forensic disciplines by finding facets of Traces in each discipline with a "common physical denominator"; this could reinforce links between forensic disciplines and strengthen forensic science foundations.

7. Conclusion

This article aims to reinforce forensic science and strengthen its foundations through a better understanding of the core concept of entity. The use of specified levels of precision when defining an entity spatially and temporally is crucial. Entities vary with the level of precision, and the relevance of alternative levels of precision vary with context of issues under consideration. Furthermore, acknowledging the subjectivity and essential mental impreciseness of the level of abstraction at which an entity is considered gives a new perspective. This article introduces the concept of *fuzzy* definition – a definition that formally includes some essential uncertainty or imprecision – in order to better grasp and describe an entity. This allows us to revisit Kirk's principle of individuality and to propose to replace it with a new principle of fuzzy unicity.

We consider that fundamental entities like (groups of) persons, objects, activities and their corresponding sources, events and traces should be fuzzy-defined. We believe that integrating such reflections in fundamental definitions will lead to the development of more faithful and relevant models by highlighting their intrinsic imprecision, their domain of application as well as some of their limits and to more transparency in communication about findings. A well-chosen level of precision for Trace-entities for example might also connect different disciplines by recognizing a common physical denominator for their typical respective Traces.

This subjectivism and impreciseness should not be misinterpreted in a way to dismiss the validity of fuzzy-defined concepts. Subjectivity only emphasizes the role and the importance of expert knowledge. As mentioned in Taroni et al. [24], "subjectivity is not a synonym for arbitrariness and […] the implementation of subjectivism does not neglect the use of the acquired knowledge that is often available in terms of relative frequencies."

As discussed, in general, no two entities in space and time should be considered identical independently of any level of precision. This echoes the message left to us by the ancient Greek philosopher Heraclitus when stating that "no man ever steps in the same river twice. For it is not the same river and he is not the same man."

CRediT authorship contribution statement

Lionel Brocard: Conceptualization, Writing – review & editing. **David-Olivier Jaquet-Chiffelle:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

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