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A formalized model of the Trace

David-Olivier Jaquet-Chiffelle*, Eoghan Casey

University of Lausanne, Batochime, Lausanne, Switzerland

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ABSTRACT

This work proposes a formalized model, grounded in forensic science, to support a unified understanding of the Trace across scientific disciplines. The model is precisely defined in mathematical terms that reflect the dynamics of an offense as expressed in Locard's Exchange principle. Specifically, this mathematical approach represents the Trace as the modification of a Scene, subsequently perceptible, resulting from the Event under investigation. Examples are provided to illustrate how this conceptualization applies to forensic science, including DNA and digital evidence. Broader implications of this model are presented in the context of COVID-19, emphasizing the value of cohesive scientific study of the Trace. The aim of this work is to stimulate more formalized study of the Trace, both from tangible and abstract perspectives, and to strengthen forensic science as a whole.

1. Introduction

Forensic science has become inordinately focused on specialized techniques that provide narrow observations in isolation, neglecting the importance of the related activity and context [1]. This tunnel vision misses the point that forensic science deals with dynamic events in elastic settings to shed light on complex questions regarding what happened, where, when, how, and sometimes who was involved and why.[1]

The central object of study in forensic science, and many other scientific fields, are *the perceptible results of an event of interest*, hereafter referred to as the Trace. The formal definition of the Trace is developed in Section 7. Capitalization is used to represent the concepts formally defined in this paper. Despite its importance, many forensic disciplines lack a precise model or a scientific definition of the Trace. In addition, each forensic discipline studies less formally defined "traces" from a highly specialized perspective, which necessarily limits the overall understanding of the Trace. A consequence of this lack of conceptual rigour is particularly pronounced when results of forensic analysis are incorrectly treated as a faithful representation of reality, or even a fact, not realizing that it is only a practical simplified conception of a partial perception of the full Trace.

The increasing emphasis in forensic science on highly specialized and controlled technological developments to analyze one specific facet of a trace diminishes the broader problem-solving potential of the Trace when studied more fully [2,3]. The combinatorial value of forensic science as a whole to comprehend the event under investigation is sacrificed by this tunnel vision within most current forensic science organizations. One facet of a trace can have different meanings depending on cohesive consideration of other facets and their context. Forensic science can be strengthened by more formalized, mathematical study of the commonalities and essential nature of the Trace to form a unified understanding.

> *The two ways of thinking (physical and mathematical): The transition from the physical to the mathematical and back again is a source of more confusion than may be suspected, but it is unavoidable. There is no doubt that the physical way of thought is the more natural, but as long as it is the only way, progress is slow. Physical things are very complicated and hard to think about. Slowly*

* Corresponding author.
E-mail address: david-oliver.jaquet-chiffelle@unil.ch (D.-O. Jaquet-Chiffelle).

[1] Forensic science has become very focused on addressing the "who" question, but the mere presence of someone's fingerprint or DNA in a place does not address the more difficult question of whether the individual was involved with the event of interest.

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Table 1
Overview of concepts defined in this work.

Concept	Summary	Scope	Section
Region	Scaffolding of location points	simultaneously belongs to all worlds	3
Scene	Content of Region in a specific world	either the tangible world or an abstract world	3
Event	Collection of completed related happenings within a specific time interval	tangible or abstract	4
Scene of Event	Scene of an Event of interest (e.g., Scene of Crime)	tangible or abstract	5
Trace	Modification of Scene resulting from Event of interest	tangible or abstract	7

we come to distinguish between properties which are essential and those which are incidental. We learn to simplify problems by forgetting the incidental properties and concentrating on those which are essential [4].

A scientific definition of the Trace is essential to advance forensic science as one science, which is more than the union of a patchwork of forensic disciplines, and to strengthen the identity of forensic science as a whole [8]. Constructing a robust theoretical model supporting forensic science reinforces its foundations as well as strengthens the confidence in its processes, therefore in its adequate practical application to real cases.

This paper is not a mathematical paper. It is a paper on the foundations of forensic science and more precisely on its core object of study: the Trace. By defining fundamental concepts in mathematical terms, this work focuses forensic science on the Trace as perceptible differences rather than a concrete thing that is only analyzed using a specialized technique. Mathematical formalism is used as a universal scientific language, in the same way that it is used in several other sciences such as physics and chemistry, to define and describe their scientific concepts. Mathematics allows a formal and unambiguous definition of the new ideas developed in this paper. However, these ideas, even the most subtle ones, can be understood without fully grasping all underlying mathematics used to formally express them.

Mathematical modeling of fundamental concepts cultivates a unified understanding of the Trace across forensic disciplines. Drawing an analogy to group theory which brings together different types of mathematical concepts (internal symmetries of a geometrical figure, permutations, etc.) into a common abstract description, a generalized common model creates links and can fuel developments in multiple fields. This is particularly important as knowledge and technology advance more rapidly, as in digital forensic science. Scientific research and advanced automated analysis methods being developed in forensic science require more refined models, which can be supported by mathematical representation.

This work presents a formalized model to support a more precise, unified understanding of the Trace across scientific disciplines. It defines the concepts in Table 1, then uses these definitions to build a unified model of the Trace of an Event which represents the underlying concepts and processes in mathematical terms.

Ultimately, what is commonly referred to as a “trace” in scientific practice is simply an observed facet of the Tangible Trace defined in Section 7.[2]

2. Related work

The importance of Events and Traces in forensic science is addressed in pragmatic terms by Locard:

The truth is that nobody can act with the intensity that a criminal action requires without leaving multiple traces of his passage. I would like to point out the extreme variety of these traces, not to write here a treatise on criminal expertise, but with the goal of demonstrating the flexibility and polymorphism of the method. The traces that I want to illustrate here are of two categories: sometimes the offender leaves at the scene the traces of his passage, sometimes, by an inverse action, he carries away on his body or clothes the traces of his stay or gesture (where he was or what he did). Deposited or received, these traces are of an extremely diverse sort. [5][3]

A précise of Locard’s principle is ***the dynamics of an offense cause traces to be exchanged between the offender(s), victim(s) and surrounding environments (physical and virtual).*** Inherent in this portrayal are differences between the state of things before and after the offense, but the lack of explicitly defined terms and concepts limits the understanding of the associated Event and Trace.[4]

A trace has been previously defined as *a mark, signal or object, the trace is an observable sign (not always visible to the naked eye), the vestige of a presence or an action at the place of the latter* [6]. This definition is rooted in the physical world and provides a strong foundation for studying traces in forensic science. Margot makes the important distinction between a visible *vestige* and non-visible *remnant* of a trace [2]. Further formalized study of the Trace can be augmented with a mathematical approach that covers all circumstances, including:

- The place where the Trace is found can coincide with the place where the event took place, but this is not always the case, particularly for digital traces (e.g., cloud traces).
- The Trace can arise from an event that is independent from a presence or action (e.g., lightening strike, earthquake, tsunami). Investigations into the cause of wild fires sometimes find the cause was a lightening strike event rather than a presence or action such as a lit cigarette or broken electrical cable.
- The Trace can arise from an interaction (e.g., gravitational or electromagnetic forces between objects, human encounters online) rather than an action.
- The Trace can be a perceptible absence of a thing that previously existed, but that was obliterated by a destructive event.
- The Trace can be ephemeral, only lasting for a short time (e.g., radio waves carrying voice communication, data in motion on a network, smells such as cleaning agents at a crime scene used by offender to destroy evidence).

Prior articulations of the process of observing and interpreting traces built on Peirce’s theoretical construct of a triadic relation

[2] The formalized model developed in this paper treats the Trace generally, and does not directly deal with its relevance to a specific scientific inquiry. A facet of the Trace of probative value in an investigation is referred to as evidence.

[3] Original French text: *La vérité est que nul ne peut agir avec l’intensité que suppose l’action criminelle sans laisser des marques multiples de son passage. Je voudrais faire toucher du doigt l’extrême variété de ces traces, non qu’il puisse s’agir d’écrire ici un traité de l’expertise criminelle, mais dans le but de montrer la souplesse et le polymorphisme de la méthode. Les indices dont je veux montrer ici l’emploi sont de deux ordres: tantôt le malfaiteur a laissé sur les lieux les marques de son passage, tantôt, par une action inverse, il a emporté sur son corps ou sur ses vêtements les indices de son séjour ou de son geste. Laissées ou reçues, ces traces sont de sortes extrêmement diverses.*

[4] A careful reader might think that “précise” was a typo. This is not the case. In a similar way, he or she might relate some of the concepts defined in this paper to his or her former knowledge too quickly. In order to minimize bias and avoid incorrect interpretation of the intertwined concepts defined in this paper, it is recommended to take time to fully grasp subtleties within each definition.

between Object-Sign-Interpretant [7]. This conceptualization has been applied to forensic science as a triad of Event-Trace-Knowledge [8–12]. Recognizing that inquiry (scientific and semiotic) requires a more dynamic approach, between 1906 and 1910, Peirce significantly extended his triadic model [13]. In this final theory of signs, called sign chains, a sign has two objects, not just one. Ultimately, Peirce perceived a sign chain progressing to an idealized conclusion, rather than an infinite semiotic process. *Peirce came to see sign theory more clearly as part of the logic of scientific discovery, and central to his account of inquiry. In particular, it led him to see sign chains (like inquiry) as tending towards a definite but idealized end*" [14].

Within a sign chain, Peirce refers to the Dynamic object as not immediately present, but rather imagined in some state prior to the inquiry process. He refers to an Immediate object perceived during the inquiry process, which is related to, and sheds light on, the Dynamic object. A sign chain can have multiple Immediate objects that relate to the singular Dynamic object, and the interpretation of the Dynamic object updates during the inquiry process as more Immediate objects are understood via their respective Signs and their signification by the interpreter (observer). *The immediate object is the object as it appears at any point in the inquiry or semiotic process. The [dynamic] object, however, is the object as it really is. [...] In other words, the immediate object is simply what we at any time suppose the [dynamic] object to be* [15].

The sign chain framework is general enough to encompass any process of scientific inquiry, and provides a strong foundation for developing a formal model of the Trace in forensic science. A "Sign of an Immediate object" is comparable to an "observed facet of a Tangible Trace" described in Section 10. However, the sign chain framework focuses on what is observed at distinct points in the inquiry, rather than on the perceptible differences (defined as the Trace in Section 7).

Peirce's sign chains defines three interpretants, rather than just one, to cover the complexity of interpretation, which is an ongoing challenge in forensic science. The present work does not address these interpretants and effects on the interpreter (observer); a comprehensive comparison between Peirce's framework and the mathematical model presented here is for future work.

Scientific study of the Trace (encompassing physical, chemical, biological and digital traces) calls for a formal model that accommodates a comprehensive set of circumstances, while making a clear distinction between tangible and abstract aspects of the Trace. This is more than a philosophical distinction between the thing-in-itself (called *Ding an sich* by Kant) and the idea or sense of the thing. Typically, scientists are multiple times removed from the Event under scrutiny, requiring them to imagine an Abstract World in which the Event occurred. The greater the separation (time and distance) and interference between the forensic scientist and the actual Event, the higher the risk of errors and omissions in understanding of the observed facets of the Trace. The formalized model of the Trace presented here is supported by a coherent set of intertwined definitions.

3. World, Region, Scene

Giving form to the scaffolding that supports everything else, we start by defining three closely related concepts: a World, a Region, and the Scene of a Region in a given World.

The *Tangible World* Ω is **the ideal representation of the world in which we live**, where observations can be made.[5] It corresponds to our whole universe with all its content, which evolves with time. In the model, at any time, the set of all location points in the Tangible World Ω is considered to be a topological space with the Euclidean topology.[6]

An *Abstract World* is **an imagined hypothetical former state** of Ω. It is a theoretical construction sharing with Ω, at any time, the same set of location points. In forensic science, the construction of an Abstract World is based on observations of Ω. One can imagine multiple different Abstract Worlds that would lead to the same observations of Ω. Consideration of alternative hypotheses is central to scientific practice.

$\mathbb{W}$ denotes a World that is either Ω or an Abstract World. All worlds in the model evolve with time and, at any time, share the same location points. However, what is observed at these location points and what happens can differ from one World to the other.

As time goes on, any set of location points usually evolves due to the dynamic nature of the universe.[7] In order to define "constant" location points at different times, we use *Simple Regions* with relative referentials that can be very rigid (e.g., for buildings) or quite elastic (e.g., for human bodies). The relative referential for a human body looks like a very fine 3-dimensional grid of coordinates, which is elastic and flexible, and that would locally stretch, rotate or compress in order to perfectly mimic movements or deformations of the body. A Simple Region for a given relative referential is an open,[8] non-empty, constant in this referential, connected set of location points in Ω, plus none, some or all its boundary points. As its interior is open and non-empty, a simple Region is a 3-dimensional "volume". At any time, any Simple Region belongs to all of the worlds (tangible and abstract) in the model, as all worlds in the model share the same location points.

In practice, a Simple Region is often a 3-dimensional volume delimited by an entity: e.g., the volume delimited by someone's body, by the interior of a car or house, by the earth, by the solar system, by the whole universe or, in the digital realm, by a mobile phone or an electronic device. The relative referential is chosen so that the points delimited by such a (sometimes dynamic) volume are perceived as constant within this referential and during the time frame pertaining to the investigation. Location points for two different values of time are considered to be the same—or more precisely *equivalent* according to a referential—if they have the same coordinates within this referential.

A *Region* is a finite union of Simple Regions. A Region is non-empty, but not necessarily connected, meaning that the Simple Regions can be separated from one another. By construction, any Region is locally constant over time with respect to some local referential, but not necessarily with respect to a unique, global referential. Indeed, the Simple Regions constituting a Region do not necessarily share the same referential; see Illustrative Example 1.

A Region can be the union of different geographical locations on Earth; it can also be the union of the volumes delimited by a set of entities, e.g. by a group of people or by a set of objects like some electronic devices. In the model, a Region is composed of location points *only*. More precisely, it does *not* contain either what is located at these location points, or the entities that have been used to delimit it. In simple terms, a Region defines the "where", not the "what". The "what is there" is the essence of another concept, namely the concept of Scene.

The *Scene* $\mathbb{S}_{R,\mathbb{W}}$ of a Region R, in a World $\mathbb{W}$ at a given time t^*, is the subset of $\mathbb{W}(t^*)$ bounded with the Region R, i.e. all content in $\mathbb{W}$,

[5] Observation involves noticing or detecting something (or its absence) in the course of a scientific study, which includes examining or measuring something.

[6] Open sets in the Euclidian topology are generated by open balls of radius $\epsilon > 0$.

[7] At a minimum, location points change as a consequence of the universe expanding.

[8] An open set according to the Euclidian topology is a set with the following property: for each point in the set, there is at least one ball of radius $\epsilon > 0$, centered at this point, completely contained in the set.

Illustrative Example 1 (Burglary) - Referentials of Region and Simple Regions

A burglary has a Region defined as the union of two Simple Regions: (1) the set of points delimited by the building and (2) the set of points delimited by the burglar's body. The first Simple Region is fixed with respect to the earth whereas the second one can move. Within a local referential of the first Simple Region (related to a building) in which all location points are fixed, the coordinates of the points delimited by the second Simple Region (related to a moving form) are not constant. To represent both the static building and dynamic burglar, their local referentials need to be different.

Illustrative Example 2 (Earthquake Damage) - Region and Scene

Consider a room in a house before and after an earthquake, and the set of all location points within this room before the earthquake. These location points constitute a Simple Region defining a static three-dimensional volume with a fixed, rigid, global referential on earth. This Region does not depend on what is in this volume. Even if the house is destroyed and the room no longer exists, the Region remains unchanged. The Scene of this Region is the evolving contents inside this volume, which is time dependent. If an object is moved out of the room, the Scene changes, but the Region does not. If the house is destroyed by an earthquake, the Scene will be completely different and, after some time, might only contain some air molecules, whereas the corresponding Region always stays the same.

Illustrative Example 3 (Homicide) - Region and Scene (Part 1)

Both Region and Scene are needed to deal with real-world dynamic situations. Consider a shooting that occurs outdoors (e.g., a wooded area). The Region can change while certain elements stay in place. For instance, the relevant Region to consider expands when bullets travel some distance away while elements of the corresponding Scene such as the victim's body remain stationary. Alternatively, the Region can remain static while elements are moved or eliminated within the Scene when the offender buries the victim's body or cleans up blood.

When a smartphone is in use by the offender and/or victim during the crime, digital traces can be transferred from a device to a remote system. For example, a mobile device connecting with a nearby cell tower transfers data to remote telecommunications systems, or a victim calling emergency services for help can capture a recording of sounds during the violent assault. These data can remain the same during the transfer while their location changes. In this case, an element of the original Scene is duplicated and the relevant Region must be expanded if it is important to include the remote system with duplicated elements.

Illustrative Example 4 (Violent Assault) - Region and Scene

During a violent assault, consider the volumes delimited by the bodies of the perpetrator and victim. Since a body is mobile and flexible, the referential needs to be local and elastic to accommodate every movement and injury. Elements of the corresponding Simple Region are not the material body (flesh, blood, bones, organs), only location points defined by coordinates. The Scene however contains all body parts and other materials inside the Region, including food in the stomach, viruses in the blood, etc.

at time t^*, located in R. Any Scene evolves and is modified as time goes on. It varies as a function of the time:

$$\mathbb{S}_{R,\mathbb{W}} = \mathbb{S}_{R,\mathbb{W}}(t)$$

A Scene in a World contains everything that belongs to this World, at the location points defined by the Region.

It is important to distinguish between a Scene, which is the set of all the located content (objects, material, smells, radio waves, etc.) in a Region in a World, and the Region itself, bounding the Scene, which is just a subset of location points without any content; see Illustrative Examples 2, 3 and 4.

In the next section, we define the concept of "event", i.e. what can impact and modify a Scene (and the relevant Region to choose), and we consider how a Scene changes over time.

4. Event

A proper definition for the Event itself is necessary prior to defining the Trace of an Event of interest. In this work, *Event E* is defined broadly as ***a complete collection of related things that have happened (or are happening) in a World within a specific closed interval of time***.[9]

The things that happen can be actions, interactions or just something happening with no actual action (e.g. the Big Bang), or even sub-events. Even in a forensic context, it is important to consider both normal and abnormal Events. Forensic science usually deals with Events that are outside the norm, including the typical criminal, civil, and regulatory functions of the legal system, as well as its extensions such as human rights, employment, natural disasters, security matters [8]. However, certain things can initially look unusual but actually are normal and, therefore, it is important to treat such Events of interest impartially. For instance, an accusation of rape can turn out to be consensual sex, or a suspected document forgery can be the result of an innocent error in updating a template, or a suspected arson may turn out to be accidental or even have a natural cause.

Completeness in this definition is theoretical, and in practice we only have an incomplete part of the collection. A collection in theory can consist of innumerable events, but in practice we limit ourselves to deemed-to-be-pertinent sub-events related to the main Event. The corresponding time interval is the smallest closed interval of time that contains the time intervals of all deemed-to-be-pertinent constitutive sub-events. As the age of the universe is finite and all considered events are past or present events, such an interval always exists.

The Event can be considered as a whole entity or as a collection of smaller sub-events. As an example, if the main Event under consideration is a specific robbery, sub-events could include "breaking into the house", "walking away from the crime scene",

[9] The interval always possesses the present time as an upper bound. Moreover, as the age of the universe is finite, the interval of time always possesses a lower bound $t_0(E)$.

“turning on the light”, “listening through the door”, “shooting at a witness”, etc. The union of two or more events can also be defined as an Event. For instance, planting an explosive device is the first event, and the subsequent explosion can be treated as a part of this initial event, or as a separate event (depending on the considered interval of time). Similarly, installation of malware with a logic bomb programmed to execute on a future date is the first event, and later the impact of the logic bomb execution can be treated as part of the initial event, or as a separate event. A coronavirus infection and growth can be investigated as a single event, or as separate events. In addition, the Event can be a combination of multiple events whose individual outcomes are no longer perceptible. Each of these combined events had its own ephemeral outcomes, but only the combined final results are perceptible as a Trace.

4.1. Intrinsic and extrinsic events

In addition to the Event of interest, it is often necessary to consider other subsequent events that influence a Scene $\mathbb{S}$ and associated Traces.

An *intrinsic event*, in the context of a Scene $\mathbb{S}$, is an event within $\mathbb{S}$ which is not an action, and that would happen even if $\mathbb{S}$ was evolving without any disturbance.

An intrinsic event happens (even) when a Scene $\mathbb{S}$ is left alone with no other influence. For example, if $\mathbb{S}$ contains a radioactive element, its natural decay is an intrinsic event (internal dynamics). Decomposition of a body is another example of an intrinsic event. Intrinsic events do not necessarily lead to an attenuation or a degradation of the Trace. For instance, when investigating how a virus arrived in $\mathbb{S}$, the subsequent viral growth and propagation in $\mathbb{S}$ is an intrinsic event. Virology and epidemiology offer interesting examples of Trace amplification and propagation (see Section 11), which play a key role in investigations of natural and manufactured biological agents. Intrinsic events comprise the interaction of the Scene with its own content. It is worth noting that such internal dynamics can vary in different Scenes, such as a chemical reaction that depends on heat or other elements present in a Scene. Furthermore, an intrinsic event can have its own Trace, and a scientist can create experiments (Section 8) that select an intrinsic event as the Event of interest. The resulting understanding of an intrinsic event can shed light on the original Event of interest and its associated Trace.

An *extrinsic event* is a non-intrinsic event, and has been referred to as *pollution* introduced to the Scene [2]. Extrinsic events that occur after the primary event of interest (e.g., a crime) is finished, regardless of intent can be caused by offenders, victims, first responders, forensic scientists and practitioners, and anyone else who has access to the Scene [16]; see Illustrative Example 5.

4.2. Shielded Scene

In practice, first responders try to prevent additional alterations of the Scene by unwanted perturbations. The aim is to forestall further modifications due to Extrinsic Events that obscure the original ones. The concept of *Shielded Scene* is introduced to represent perfect preservation of the Scene, i.e. ideal protection of the Scene against external perturbations.

A *Shielded Scene*, against a set of extrinsic events, is an imagined Abstract Scene which would be fully protected against any impact of these extrinsic events. In other words, a Shielded Scene lives in an Abstract World where these extrinsic events cannot modify the Scene.

5. Scene of Event

Whether it be a crime, accident, natural disaster or some other happening, an Event modifies the World (tangible or abstract) in which it happens. In other words, modifications of the Scene will occur as a result of the Event.

*A **Scene of Event** is a Scene (located content)* related to the Event of interest. As with any Scene, it is bounded by a Region.

A Scene of Event usually evolves with time due to internal dynamics and external influences (e.g., contamination, pollution). Its bounding Region—or some of the locally constant Simple Regions constituting it—may also evolve with respect to a more global referential.

5.1. Crime scene and Scene of Investigation

The *crime scene* is typically defined intuitively as “the scene where the crime (or Event of interest) happened”. The exact geographical limit of the crime scene is not defined precisely enough, and what is considered to be the crime scene can slightly vary from one scientific investigator to another. Therefore, it is not unique. For a given crime, we should consider ***a*** corresponding crime scene rather than ***the*** crime scene.

In forensic science, a *Crime Scene* is a Scene bounded by a “small” Region in which the Event of interest (e.g., crime, accident, disaster) happened, if such a precise Region exists. Indeed, such a precise Region does not always make sense: consider for example the single criminal Event corresponding to an activated logic bomb in the Cloud.

A *Scene of Investigation* is bounded by a Region that is considered relevant for observing results of the Event of interest. The Region corresponding to a Scene of Investigation is typically broader than the one associated with a Crime Scene. Indeed, results of the Event of interest can spread away from the original Crime Scene. The Region associated with the Scene of Investigation is defined as the Region that is deemed-to-be-pertinent for observing consequences of the Event of interest. When choosing a Scene of Investigation, there is a trade-off between retaining a larger Region with more information to deal with, versus a smaller Region, whose corresponding Scenes will be easier to investigate, but with the risk of missing consequences resulting from the Event of interest. The Region associated with the Scene of Investigation can be restricted by other factors such as legal jurisdiction.

The Region defining the Scene of Investigation will typically include geographical locations of interest, the volumes delimited by the bodies of victims and offenders, the volumes delimited by some of their belongings. Geographical locations do not need to be connected or next to each other.

In case of a digital investigation, the Region defining the Scene of Investigation typically includes the volumes delimited by a set of considered-to-be-pertinent electronic devices: mobile phones, computers, servers, or other connected objects in the Internet of Things (IoT). It may also include volumes delimited by the communication channels and cloud services interconnecting some or all of these devices.

Illustrative Example 5 (Homicide) - Intrinsic and Extrinsic Events (Part 2)

Continuing the example of a homicide in which the victim is wounded before death, blood dripping from the victim’s wound is an intrinsic event. This is due to internal dynamics caused by gravity. A first responder moving the body while attempting to resuscitate the victim is an extrinsic event. Someone subsequently entering the scene with a mobile device that interacts with the environment and nearby devices is an extrinsic event.

5.2. Tangible versus Abstract Scenes

Forensic science is mostly practical, and is primarily concerned with the perceptible results of a completed Event of interest, such as a crime, accident, security incident, or natural disaster. However, because forensic scientists are typically not at a crime scene while the offense is being committed, they are separated by time, and sometimes distance, from the associated Event(s) and consequences, in particular, the associated Trace as defined below in Section 7. As a result, forensic scientists must imagine possible Abstract Worlds in a hypothetical former state in which alleged Event(s) occurred or not.

We can particularize our definition of Tangible World and Abstract Worlds to their subsets:

- A *Tangible Scene* is a Scene belonging to the Tangible World Ω.
- An *Abstract Scene* is a Scene belonging to an Abstract World. It is an imagined Scene in a hypothetical (former) state; see Illustrative Example 6.

6. Categories of modifications

Events modify their Scenes. Modifications can be described from several perspectives and levels of abstraction. Specifying the concept of modification makes it easier to articulate the impacts of the Events under consideration. Indeed, naming and classifying allows useful simplification. In this section, we describe three fundamental categories of modifications: *adjunction, suppression, and change.* Any modification can be decomposed into sub-modifications belonging to exactly one of these three categories at a certain level (macro, meso, micro or nano). However the decomposition is not necessarily unique. Indeed, the same modification can sometimes be expressed in more than one way, as different combinations of adjunctions, suppressions, and changes. Sub-categories of the latter category—-*transformation, change of state or property*—allow a more precise description of some changes, in particular discrete ones. We also consider secondary categories that combine the fundamental ones and might be more efficient to describe some modifications more concisely: *move, replace,* etc. All modifications are combinations of the fundamental categories. Depending on the precision and abstraction level that is considered for the observation, we might qualify the modification using—amongst all possible fundamental or secondary categories—the category that best describes the aspect we consider to be most relevant.

6.1. Adjunction

The Event causes some content of the Scene to be increased or added. Examples of adjunction in a forensic science context at a macro, meso or micro level:

- abandoned object, deposited matter (e.g., DNA, microtraces, gunshot residue);
- smell, background radiation, etc.
- file saved onto a computer, computer infected by malware, log entry of a logon to an Internet server;
- data generated within a cloud environment, stored on some server at an unknown location.

At the atomic level, if we consider a “nano” Scene, delimited by a tiny Simple Region containing a location point, some atoms or molecules can be added as a consequence of the Event.

6.2. Suppression

The Event causes some content of the Scene to be diminished or suppressed. Examples of suppression in a forensic science context at a macro, meso or micro level:

- stolen object;
- file wiped from a computer;
- malware obliterated by antivirus software;
- deleted log entries or disabled logging on a server;
- storage media removed from a computer and destroyed.

At the atomic level, if we consider again a “nano” Scene, delimited by a tiny Simple Region containing a location point, some atoms or molecules can be removed as a consequence of the Event.

6.3. Change

The Event causes some content of the Scene to be changed. Change at a macro or meso level can often be considered as the global result of numerous adjunctions, suppressions and/or changes at the micro or atomic level.

6.3.1. Transformation

Examples of transformations in a forensic science context at a macro, meso or micro level:

- shoe impression of a shoe sole in the ground (mechanical transformation);
- damaged area on a shoe sole itself;
- sound wave (pressure change);
- environmental change (temperature, moisture);
- aging of an object;
- data having been encrypted;
- file altered on a computer, altered logs on a server (digital transformation).

At the atomic level, if we consider again a “nano” Scene, delimited by a tiny Simple Region containing a location point, a chemical reaction can transform some atoms or molecules as a consequence of the Event.

Illustrative Example 6 (Homicide) - Tangible versus Abstract Scenes (Part 3)

Imagining multiple different Abstract Scenes is an integral part of scientific practice, necessary for the evaluation of alternative hypotheses. Continuing the example of a homicide, forensic scientists treat the Crime Scene after intrinsic events (e.g., blood dripping, decomposition) and extrinsic events (e.g., first responder actions). On the basis of observations of the Tangible Scene, they envision various Abstract Scenes in their mind. For instance, they imagine possible positions of the victim’s body at the time of the crime, and consider whether specific marks on the victim’s body existed prior to the crime, or were caused by the crime, or were due to first responder actions. In addition, as they scrutinize the Scene of Investigation, they imagine Abstract Scenes with possible content such as the weapon, offender DNA in certain locations, and associated digital evidence. They then check the Tangible Scene for the presence of such possible content.

6.3.2. State change

The Event causes a change of state—a discrete change usually at a more abstract level—within the Scene. The list of possible states is typically finite. Being considered in one state or the other may depend on a threshold. Examples of state change in a forensic science context at a macro, meso or micro level:

- open/closed door;
- hot/cold environment (temperature states);
- alive/dead (person, animal);
- modification of access rights (of a building, of a digital file);
- file marked as deleted on a computer;
- encrypted/unencrypted data.

At the atomic level, quantum physics allows distinct states for a particle. In an investigation involving quantum cryptography, a change of state could mean that the polarization of a photon has changed or that two former intricated particles are not intricated anymore, as a consequence of the Event of interest.

6.4. Combination of previous categories

The *move* of an entity as a consequence of an Event can be seen as the suppression of the entity in some small Scene and the adjunction of it in another one. However, if the entity stays in the Scene under consideration it might be simpler to describe the modification as a move. Examples of moves in a forensic science context:

- moved knife within the Crime Scene;
- dust from the Crime Scene having been transferred to the coat of a suspect;
- malware quarantined by antivirus software;
- moved file from one directory to another one in a computer.

Many modifications actually are a (sometimes complex) combination of the previous categories. Replacing a masterpiece of art with a fake copy can be decomposed as a combination of a suppression and an adjunction, a.k.a. substitution, a common feature or observation in questioned document examination (QDE).

The modification corresponding to the move of an object might also comprise some adjunction (DNA of the person who moved the object deposited on its surface), some suppression (color pigments of the surface of the object transferred onto the hand of the person who moved it), and the movement of air particles.

The main qualification of the modification may depend on the abstract entity that is observed, as well as on the precision and abstraction level that is considered to be the most pertinent for the observation.

7. Trace

Using the previous definitions, we propose an intuitive, formal, unified definition of the Trace of an Event:

From a conceptual perspective, the *Trace* of an Event E within a region R is ***the full modification of the Scene $\mathbb{S}$ bounded by R, resulting from the Event E, completed or not, and subsequent intrinsic events.***

Any part of this modification is called *a facet of the Trace.* What forensic science commonly refers to as a “trace” is only one aspect of the full modification of a Scene of Investigation, i.e., a facet of the Trace.

More precisely, the Trace is defined as a *difference* between two Scenes $\mathbb{S}_{R,\mathbb{W}_E}(t)$ and $\mathbb{S}_{R,\mathbb{W}_{\neg E}}(t)$ respectively within two Abstract Worlds—$\mathbb{W}_E$ and $\mathbb{W}_{\neg E}$—which are identical to the Tangible World Ω until $t_0(E)$, the very beginning of the Event E.

In $\mathbb{W}_E$, the event E happens. After $t_0(E)$, the Scene $\mathbb{S}_{R,\mathbb{W}_E}$, bounded by R, is shielded against any new events, except for its own intrinsic events and the direct consequences of E. In the World $\mathbb{W}_{\neg E}$, the event E however is supposed not to happen. In $\mathbb{W}_{\neg E}$, after $t_0(E)$, the Scene $\mathbb{S}_{R,\mathbb{W}_{\neg E}}(t)$, bounded by R, is shielded against any events, except for its own intrinsic events.

The Theoretical Trace of the Event E within the region R is defined for $t > t_0(E)$ using Δ, the *exact difference* [10] operator:

$$\textbf{Theoretical Trace}(t) = \Delta\left(\mathbb{S}_{R,\mathbb{W}_E}(t)\ ;\ \mathbb{S}_{R,\mathbb{W}_{\neg E}}(t)\right),\ t > t_0(E)$$

Of course, intrinsic events—both in $\mathbb{W}_E$ and in $\mathbb{W}_{\neg E}$ —can modify the Theoretical Trace as time goes on. This gives the Theoretical Trace its internal dynamics (e.g., internal decay, wave propagation).

In essence, the Theoretical Trace is intrinsically linked to the Scene in which it manifests and with which it interacts.

Note that this definition is purely theoretical as we can imagine that almost everything could change, even if only infinitesimally, as a consequence of the event.[11] Most of these differences would be impossible to perceive.

Even though this intuitive, formal definition of the Theoretical Trace might be interesting from a philosophical perspective, its very strict concept of “difference” prevents this definition to fit the practical needs in (forensic) science. It is necessary to find a way to eliminate “infinitesimal”—deemed-to-be-irrelevant—differences in the definition of the Trace.

7.1. Perceptible differences

In forensic science, as well as in other scientific disciplines, we are interested in perceptible differences up to a certain precision. The term *perceptible* is used here to describe a difference that could be discerned by the senses, either directly or using an instrument, now or in the future. In some situations, a perceptible difference cannot be observed because a suitable measuring instrument has not been invented yet, is too expensive, or is unavailable for some other reason; see Illustrative Example 7.

Modeling the concept of *perceptible difference* in a mathematical way, is tricky. First we need to grasp the concept of *sameness* in this context, in order to define the complement of a perceptible difference. The mathematical concept of *tolerance relation* will help us. A tolerance relation over a set of elements is a relation defined between the elements of this set which is:

- reflexive (any element is in relation with itself),
- symmetric (if x is in relation with y, then y is in relation with x),
- not always transitive (there is x, y and z such that x is in relation with y, y is in relation with z, but x is <u>not</u> in relation with z).

In other words, even when x is in relation with y and y is in relation with z, x is not necessarily in relation with z. A tolerance relation is not as strong as an equivalence relation which *is* always transitive. However, it captures very well the principle of *resolving power* of a microscope, or of any technical instrument used to observe a Trace.

First, we consider a gigantic set $\mathscr{C}$: the union of all possible located contents (perceptible or not) of all possible worlds (tangible or abstract). Scenes are constituted of located content. Therefore, any Scene $\mathbb{S}(t)$ is a subset of $\mathscr{C}$.

[10] The *exact difference* operator takes absolutely all modifications, perceptible or not, into consideration. Even infinitesimal modifications, at sub-atomic level for example, impact the exact difference.

[11] Edward Lorenzo’s so-called butterfly effect suggests that even a “small” event has an impact, almost imperceptible, on everything [17].

Illustrative Example 7 (Homicide) - Perceptible Differences (Part 4)

Continuing the example of a homicide, many modifications of the Crime Scene due to the Event of interest are not perceptible. Such imperceptible modifications can be biological material (e.g., contact DNA, latent fingermark) scattered among leaves and dirt, or molecules having moved; a digital signal sent via radio waves which is neither intercepted, nor recorded, quickly becomes not perceptible.

A *precision p* is a symmetric function from $\mathscr{C} \times \mathscr{C}$ to $\{0, 1\}$:

$$p:\ \mathscr{C} \times \mathscr{C} \longrightarrow \{0, 1\}$$

$$(c_1; c_2) \longmapsto p(c_1, c_2) = \begin{cases} 1 & \text{if a difference between } c_1 \text{ and } c_2 \\ & \text{can be perceived according to } p \\ 0 & \text{otherwise} \end{cases}$$

For any precision function p and for all $c \in \mathscr{C}$, $p(c, c) = 0$.

The precision function p corresponding to the exact difference operator satisfies $p(c_1, c_2) = 0$ if and only if $c_1 = c_2$. For this function, any difference is perceptible. This particular case corresponds to the Theoretical Trace.

Two different precision functions p_1 and p_2 cannot be compared in general. However, if the Kernel of p_1 is contained in the Kernel of p_2, i.e. if $p_1^{-1}(0) \subset p_2^{-1}(0)$, then p_1 is more precise than p_2. The precision function which always returns 0 is the least precise one: no difference can be perceived according to this precision function.

Practical precision functions are defined over a subset of $\mathscr{C} \times \mathscr{C}$. They can use thresholds either arbitrarily chosen, or derived, for example, from the resolving power of possible observation tools. There are infinitely many possible precision functions.

Then, given a precision function p, we define a tolerance relation over $\mathscr{C}$ at precision p:

Two elements c_1 and c_2 in $\mathscr{C}$ are p–related if ***no difference*** *can be* ***perceived*** *between c_1 and c_2 with respect to precision p*, i.e. *if $p\ (c_1, c_2) = 0$.*

Eventually, for a Scene $\mathbb{S}(t)$ and a given precision p, we define an extended scene with respect to this precision $\tilde{\mathbb{S}}(t, p)$:

$$\tilde{\mathbb{S}}(t, p) = \{\tilde{c} \in \mathscr{C} \mid \exists\ c \in \mathbb{S}(t) \quad \text{such that } c \text{ is } p\text{-related to } \tilde{c}\}$$

Intuitively, $\tilde{\mathbb{S}}(t, p)$ is a huge abstract Scene containing $\mathbb{S}(t)$, as well as all possible located content which would not be distinguishable (no perceptible difference at precision p) from some located content of $\mathbb{S}(t)$.

This allows to define an operator $\tilde{\Delta}_p$, *difference with respect to the tolerance relation at precision p*, between any two Scenes bounded by the same Region *R*.

More precisely, for any time t, given two Scenes $\mathbb{S}_1(t)$ and $\mathbb{S}_2(t)$—respectively in $\mathbb{W}_1(t)$ and $\mathbb{W}_2(t)$—bounded by *R*, we first calculate:

- $\mathbb{S}_1(t) \cap \tilde{\mathbb{S}}_2(t, p)$, the set of elements in $\mathbb{S}_1(t)$ which are not distinguishable from elements of $\mathbb{S}_2(t)$, and
- $\mathbb{S}_2(t) \cap \tilde{\mathbb{S}}_1(t, p)$, the set of elements in $\mathbb{S}_2(t)$ which are not distinguishable from elements of $\mathbb{S}_1(t)$.

Then those sets of *not distinguishable elements* are used to keep only the perceptible differences between $\mathbb{S}_1(t)$ and $\mathbb{S}_2(t)$. These perceptible differences $\mathbb{S}'_1(t, p)$ and $\mathbb{S}'_2(t, p)$ are defined as follows:

$$\mathbb{S}'_1(t, p) := \mathbb{S}_1(t) \setminus (\mathbb{S}_1(t) \cap \tilde{\mathbb{S}}_2(t, p))$$
$$\mathbb{S}'_2(t, p) := \mathbb{S}_2(t) \setminus (\mathbb{S}_2(t) \cap \tilde{\mathbb{S}}_1(t, p))$$

where the symbol \ denotes a substraction between two sets.

Eventually, the *perceptible difference* operator is defined by:

$$\tilde{\Delta}_p(\mathbb{S}_1(t)\ ;\ \mathbb{S}_2(t)) := (\mathbb{S}'_1(t, p)\ ;\ \mathbb{S}'_2(t, p))$$

It is important to emphasize that the perceptible difference has two components: $\mathbb{S}'_1(t, p)$ which belongs to $\mathbb{S}_1(t)$, and $\mathbb{S}'_2(t, p)$ which belongs to $\mathbb{S}_2(t)$.

As an example, let us consider an object which is removed from a Scene. We consider $\mathbb{S}_1(t)$ the hypothetical Scene where the object has not been removed, and $\mathbb{S}_2(t)$ the actual Scene where the object has been removed. The object is perceptible as present in $\mathbb{S}_1(t)$, but neither in $\mathbb{S}_2(t)$ nor in $\tilde{\mathbb{S}}_2(t, p)$ anymore. Consequently, it is not in $\mathbb{S}_1(t) \cap \tilde{\mathbb{S}}_2(t, p)$ and therefore stays in $\mathbb{S}'_1(t, p) = \mathbb{S}_1(t) \setminus (\mathbb{S}_1(t) \cap \tilde{\mathbb{S}}_2(t, p))$. It is absent in $\mathbb{S}'_2(t, p)$.

Similarly, if an item is added to the Scene, it is absent in $\mathbb{S}'_1(t, p)$ and present in $\mathbb{S}'_2(t, p)$.

7.2. Abstract Trace

In order to only consider perceptible differences and head towards a unified definition of the Trace that fits the scientific requirements, we propose the following definition:

Given a precision p of perception, the *Abstract Trace* of an Event within a region *R* is ***the full modification of the Scene bounded by R, subsequently perceptible, resulting from the Event E, completed or not, and subsequent intrinsic events.***

We keep the same Abstract Worlds—$\mathbb{W}_E$ and $\mathbb{W}_{\neg E}$—as before. However, the Abstract Trace is now the *perceptible* difference at precision p between $\mathbb{S}_{R,\mathbb{W}_E}(t)$ and $\mathbb{S}_{R,\mathbb{W}_{\neg E}}(t)$, without the myriad imperceptible modifications.

In the context of forensic science, the Abstract Trace in a Scene of Investigation is ***the perceptible modification of the Scene of Investigation resulting from the completed Event of interest and subsequent Intrinsic events (internal dynamics of the Scene of Investigation)***.

From an intuitive perspective, the $\Omega_{\neg E}$ operator produces the perceptible difference between $\mathbb{S}_1$ and $\mathbb{S}_2$. This operator allows to formally define the *(perceptible) Abstract Trace* of an Event *E* within a Region *R*:

$$\textbf{Abstract Trace}(t, p) = \tilde{\Delta}_p\left(\mathbb{S}_{R,\mathbb{W}_E}(t)\ ;\ \mathbb{S}_{R,\mathbb{W}_{\neg E}}(t)\right),\ t > t_0(E)$$

An Abstract Trace is typically idealized and imagined. As for the Theoretical Trace, it is a function of the time. This captures in particular the internal dynamics of a Scene, like the concentric waves moving on the surface of a lake after we throw a stone. The Abstract Trace is still very theoretical as we suppose that, next to the Event *E* itself, no extrinsic event takes place after $t_0(E)$.

7.3. Tangible Trace

The Abstract Trace differs from what is actually observable in the Tangible World consequently to the Event of interest, because extrinsic events happening after $t_0(E)$ usually alter what is observable. Therefore we need to define the *Tangible Trace*, perceptible in the Tangible World Ω.

More precisely, in order to define the Tangible Trace of an Event *E*, we consider two worlds: the World Ω and an Abstract World $\Omega_{\neg E}$ where the event *E* (and any sub-events) would not have happened. The Tangible Trace of an Event *E* within a Region *R* is define using again the perceptible difference operator:

Illustrative Example 8 (Homicide) - Tangible Trace (Part 5)

> Continuing the example of a homicide, there could be a number of explanations for the presence of a person's DNA on the trigger of a weapon at the Crime Scene. To eliminate possible explanations, forensic scientists consider whether the gun is the murder weapon (Was another gun used to shoot the victim?), whether a suspect's hand has gunshot residue (Did the suspect fire a gun?), whether there is any blood from the victim transferred onto the suspect (Were the suspect and victim next to each other when the victim was shot?), whether the suspect's mobile device was nearby (Was the suspect's mobile phone at the Crime Scene at the time of the crime?), and any other – expected or not – perceptible differences that can address the problem.

$$\textbf{Tangible Trace}(t, p) = \tilde{\Delta}_p(\mathbb{S}_{R,\Omega}(t)\ ;\ \mathbb{S}_{R,\Omega_{\neg E}}(t)),\ t > t_0(E)$$

This formalized definition reflects the essential nature of the Tangible Trace as a perceptible difference rather than a concrete thing. This unifying model of the Tangible Trace reveals several other characteristics of its nature:

- **Conceptual** – although tangible and perceptible, it is just out of reach of full comprehension, solely existing as a conception of our minds.
- **Relative** – it is defined with respect to a relative parameter p, the level of precision below which differences are considered to be imperceptible: what is perceptible and what is not depends on the accepted/decided precision threshold.
- **Practical** – the "trace" as it is generally referred to in practice is simply an observed facet of the Tangible Trace.
- **Camouflaged** – the concrete observed facets (discussed in Section 10) of the Tangible Trace encourage tunnel vision, diverting attention from its core and full nature, its properties, and how it works.
- **Partially perceived** – it can only be partially perceived through its observed facets. Consequently, forensic scientists and practitioners, as well as investigators, prosecutors, lawyers, judges, court experts and people in a jury must be cognizant that our understanding of the Tangible Trace is never complete.
- **Dynamic** – it is a function of the time. In particular, the internal dynamics of the Scene make the Trace evolve as time goes on, even without extrinsic events.

Highlighting the broader problem-solving potential of the Trace when studied more fully, Margot notes its conceptual, dynamic, and partially perceived nature:

> *The information content of this vestige may be sufficient to identify its source (such as with DNA, fingermarks, toolmarks, etc.), to specify the 'presence' or 'existence' of 'someone' or 'something', but it also gives information related to space (where and how-orientation, action, electronic connection, images) and time ('initially' or when, succession, sequence, communication, etc.) to describe the overall activity that created the trace. Since it is not possible to go back in time, we can only construct a model that is descriptive of a given crime scenario, supported by what is observed. This is not a general model, but a specific retrodictive model that can only be probabilistic in nature. In the majority of cases, the quality of the vestige is such that it is incomplete, imperfect and degraded by time passing, and these losses increase uncertainty or may support only approximations about the past event. These approximations need to be revised as new or complementary information becomes available. This may be unsettling for scientists focused on the precision and accuracy of measurements* [2].

Challenges met in constructing and revising a partial retrodictive model are compounded by the tunnel vision of refining highly specialized techniques to analyze one specific facet of a particular type of the Trace. This tendency to answer the easier question has been termed attribute substitution, *when confronted with a difficult question people often answer an easier one instead, usually without being aware of the substitution* [18,19].

The increased sensitivity of DNA profiling has become extremely effective for determining who was present at a Scene, but has diverted attention from its context and problem solving potential [2]. In addition to identifying the source of a DNA profile found at a Scene, in many cases the forensic question to be addressed is the probability of the material being found at the Scene in given scenarios (activity level propositions help here).

With DNA, the Trace is the adjunction of some biological material at a specific location in the Crime Scene, not just the DNA itself. Although Touch DNA takes into account dynamics, this specialized technique can still suffer from tunnel vision, diverting attention from the essential nature of the Tangible Trace. Usually, DNA found at a crime scene is just one of many differences between the Tangible World and an Abstract World. It is also important to note that DNA may only be partially perceived via its observed facets, including its biological components, its digital representation, and the associated profile. To make effective use of forensic science, it is necessary to consider the many differences forming the Trace, and not to focus narrowly on just one; see Illustrative Example 8.

Treating a characteristic of the DNA by itself as a concrete thing rather than conceptualizing the Tangible Trace more broadly as the perceptible difference limits our comprehension of its nature and broader problem-solving potential. Furthermore, leaving the more complex forensic questions unanswered in an investigation increases the risk of confusion and misinterpretation by decision makers when they attempt to reach conclusions based on forensic findings.

> *The role of the forensic scientist [is] to provide as much guidance to the trier of facts if the knowledge he/she may bring is outside the general knowledge of the court and relevant to the task at hand. Shying away from this duty on the ground that considerations regarding transfer of trace DNA is less known than source level DNA statistics is not acceptable. There is a risk with leaving the presence of DNA to be assessed by others, left to advocacy, when the scientist can bring decisive knowledge, including highlighting how complex the task may be. We want to avoid the simplistic line of argument that I have heard at times: "We have found DNA corresponding to the defendant on the trigger of firearm, hence he manipulated the gun." It is crucial for a fair administration of justice that forensic scientists weigh their expectations of the amount of DNA recovered given both views. Hence scientists' guidance is required when the consideration of transfer mechanisms, persistence and background levels of the material has a significant impact on the understanding of the alleged activities and requires expert knowledge* [20].

8. Experimental study of Traces

Scientists sometimes try to simulate what they observe, performing experiments in a controlled environment to increase their knowledge and understanding, and ultimately regard the simulation as a reasonable representation. A *Simulated Trace* is ***a special case of Tangible Trace where the Event of interest is provoked by the scientists in a controlled environment and can be repeated.*** When forensic scientists do not know specifically what Event occurred, they must imagine (hypothesize) various Abstract Worlds and Events. Then they must compare the simulated experimental

Illustrative Example 9 (Physical Scene of Investigation) - Observation Instruments

A man is suspected of killing his wife in their home and hiding her body. A strong smell of cleaning agent is perceptible during a search of the house. A cadaver dog has a positive alert in the kitchen and the trunk/boot of his car. Luminol tests reveal vestiges of blood (hemoglobin) on the kitchen floor. Closer examination of the kitchen finds a blood spatter pattern on one wall cabinet explained by head impact. DNA tests indicate that the blood on the kitchen floor and wall was the wife's.

results–the observed facets of some Simulated Traces–with observed facets of the Tangible Trace of the Event under investigation. In addition, forensic scientists often attempt to apply understanding of Abstract Traces derived from observed facets of Simulated Traces in controlled experiments to interpret the Tangible Trace of the Event under consideration. Experiments in a controlled environment are closer to studying hypothetical states of the Trace, because it is not feasible to simulate the Crime Scene exactly. The formalized model presented in this paper helps differentiate between the Tangible Trace, the study of Abstract Traces through Simulated Traces in controlled experiments, and their respective observed facets.

9. Observation instruments

Perceptible differences are not always discernible *directly* by the observer's own senses. In some cases, an instrument is required to observe a perceptible difference of a Scene. Forensic scientists rely on specialized observation instruments to discern certain kinds of perceptible differences. The case scenario in Illustrative Example 9 provides examples of observation instruments used at a physical Scene of Investigation.

In the above case scenario, investigation observation instruments (cadaver dog, luminol, DNA test) are used to reveal not directly discernible differences of the Scene (cadaver smell, hemoglobin, DNA) that might shed light on a significant directly perceptible difference of the Scene—the wife's body is absent.

The case scenario in Illustrative Example 10 provides examples of observation instruments used at a digital Scene of Investigation.

In the above case scenario, observation instruments are used to uncover perceptible differences (facets of the Tangible Trace) in a digital Scene of Investigation that shed light on perceptible differences in a physical Scene of Investigation. Another example of this interaction between physical and digital is provided in the following case scenario described in Illustrative Example 11, with the Event encompassing multiple sub-Events.

Keep in mind that even the most sophisticated scientific observation instruments can only be used to discern a perceptible difference partially at a specific moment in time, i.e., an observed facet of a Tangible Trace.

10. Observed facets

When scientists study a Trace (tangible or simulated), only certain facets are observed, and other facets remain unobserved due to lacking knowledge, methods, technology, or resources. Scientists can also overlook certain facets as a result of cognitive bias or not asking the right question [22]. An observed facet can include sound, smell, or other measurable features.

In practice, a Trace (tangible or abstract) is very often described according to a particular observed facet and the perspective that is chosen to observe this facet. This perspective is either expressed according to properties of the observed facets (*biological* trace, micro trace, paint trace, digital trace) which is actually only part of the Trace itself, or according to the nature of the supposed entity that generated the Trace (shoe trace, tool trace). This abuse of language is current and useful, but should not prevent forensic scientists from studying the full Trace using its formalized definition with the aim of achieving a more unified and comprehensive understanding.

10.1. Chemical observed facets

The chemical Tangible Trace is defined as *the chemical modifications of the Scene, subsequently perceptible, resulting from the Event of interest and subsequent intrinsic events.* Let us think about a drug test as testing a difference between the Tangible World and an Abstract World. A forensic scientist observes the GC-MS results of a urine sample in the Tangible World and compares them to properties of clean urine in an Abstract World in which there would be no drug. In this case, the "traces" as it is commonly known is an observed facet of the difference between the urine sample and clean urine. In order to classify or identify the drug, the forensic scientist compares the GC-MS results of the urine sample with experiments on known exemplars under controlled conditions (Simulated Traces); see Illustrative Example 12.

10.2. Digital observed facets

The digital Tangible Trace is defined as *the modifications of the Scene, subsequently perceptible in binary form, resulting from the Event of interest and subsequent intrinsic events.* An observation instrument

Illustrative Example 10 (Digital Scene of Investigation) - Observation Instruments

A man is suspected of poisoning his wife with antifreeze. Medical examination indicates that the victim was poisoned. Digital forensic scientists perform keyword searches on computers found in the home and find the phrase "ethylene glycol death human" in deleted remnants of Internet search history [21].

Illustrative Example 11 (Digital-Physical Scene of Investigation) - Observation Instruments

Remains of a murder victim's body are found in the woods with marks on her bones indicative of stabbing. Digital forensic examination of a suspect's mobile device recovers deleted multimedia messages (MMS) to the victim. These Traces of other, possibly anterior, sub-Events bring a new perspective on the main Event of Interest. The text of messages state that the suspect intends to stab the victim for sexual gratification. Attached videos show scenes of piquerism. Digital forensic examination of the suspect's computer and online activities find that he was involved in bondage, dominance and sadomasochistic activities, particularly piquerism.

Illustrative Example 12 (Drug Analysis) - Observed Facets

> Drug analysis can involve finding a substance in solid form or in a person's body. In solid form, a forensic scientist can observe the color, smell, and texture. In a urine sample, many of these facets of a drug cannot be observed. Forensic methods, such as immunoassay and chromatography-mass spectrometry (GC-MS), can be used to observe other facets of a drug. The representation of GC-MS output in digital form can be viewed as the result of the observation of another facet. The effectiveness of such forensic observation methods depends on the environment, e.g., body weight, level of hydration, time after ingestion, temperature.

is always required in the digital realm because it is not feasible to observe data directly. A digital Tangible Trace on a computer hard disk has several facets that can be observed at the physical level, binary level, application level, semantic level, as shown in Fig. 1. Some facets of a digital Tangible Trace might only become observable and meaningful in the future, such as encrypted data that currently resists decryption.

There are two aspects of the digital domain that highlight the nature of the Trace and the importance of the formalized model in this work to avoid misconceptions and misinterpretations of the full Trace.

First, digital devices and sensors record so many details about their use and surroundings that subsequent observation of these data can be incorrectly treated as a faithful representation of reality,

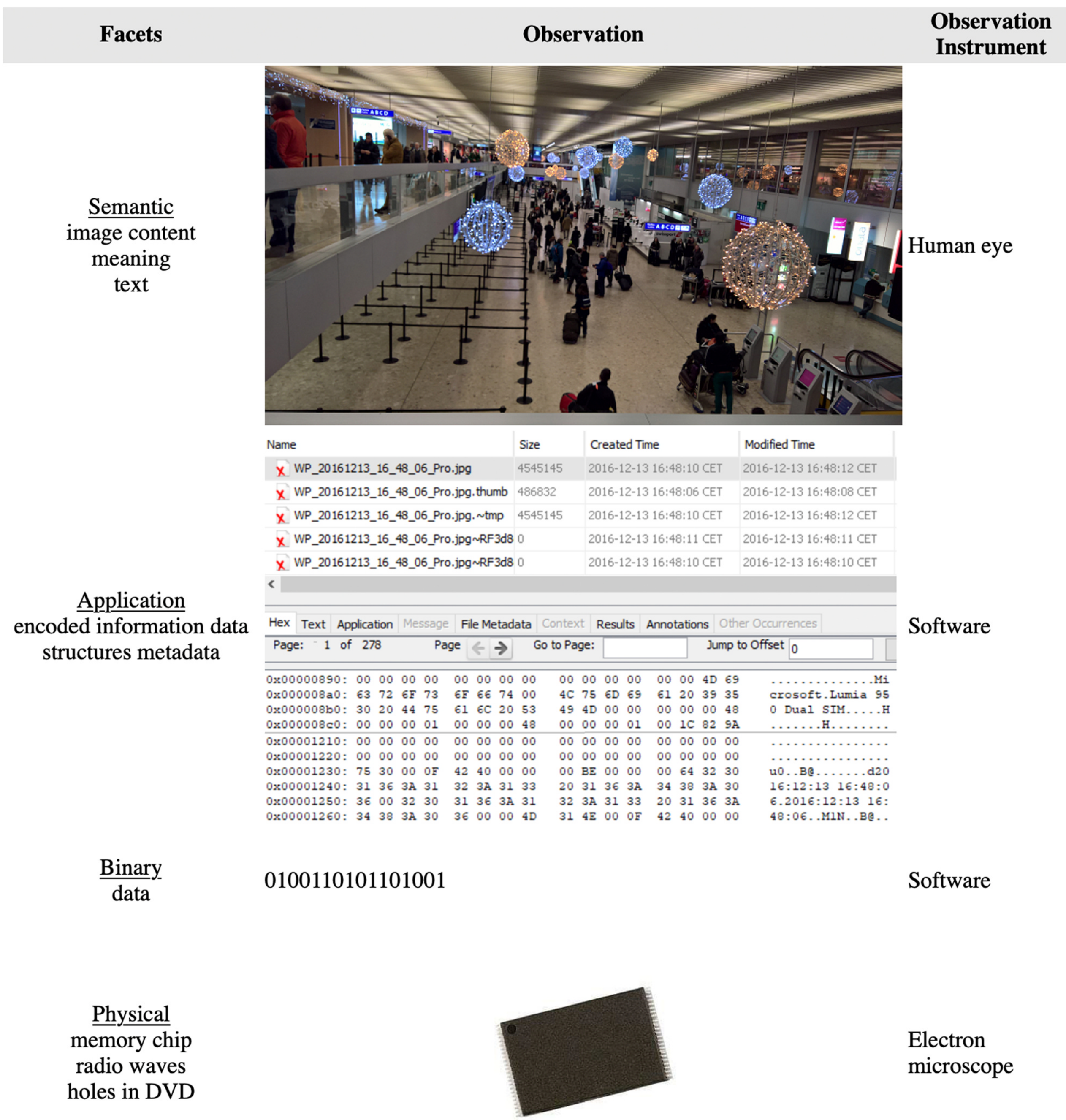

Fig. 1. Different observation levels of the Trace.

Table 2
COVID-19 pandemic.

Concept	Description
Event	Collection of completed happenings directly related to the outbreak of COVID-19 pandemic in a world within a specific time interval
Region	3-D grid encompassing the entire Earth globe (without its content) in all Worlds
Scene of Event	Globe region and its complete contents in a specific World
Trace	Perceptible modification to the Scene of Event resulting from the collection of completed happenings directly related to the Event under consideration (outbreak of COVID-19 pandemic within the chosen time interval)
Intrinsic events	Propagation of COVID-19 contagion within the Scene of Event, including COVID-19 patients having symptoms and people dying from COVID-19, but also non-coronavirus related events such as ocean tides and Carbon-14 natural decay
Extrinsic events	Social distancing, travel restrictions, quarantine, sanitization, as well as all events unrelated to COVID-19, including those outside the Earth globe, such as solar influences

Table 3
COVID-19 infection.

Concept	Description
Event	Initial infection in a body within a specific time interval
Region	Elastic flexible 3-D grid that wraps around and moves with the infected body
Scene of Event	Content of the infected body in a specific world
Trace	Perceptible modifications to body due to COVID-19 initial body infection
Intrinsic events	Internal dynamics of COVID-19 and infection growth within body, as well as all non-coronavirus related normal happenings in the body
Extrinsic events	Medical treatment of COVID-19 infected body, as well as any external event or action – not necessarily coronavirus related – impacting the body

Illustrative Example 13 (Virus Infection) - Epidemiology (Part 1)

The Event of interest is the initial infection of a group of people; the typical duration of the chosen time interval varies between a couple of minutes up to a few hours, or even a few days. The Scene (of investigation) $\mathbb{S}$ is broader than the union of the bodies of originally infected individuals. The Scene also contains objects and surfaces that can be touched or contaminated, and even the ambient air volume that can contain the virus. The Tangible Trace is not limited to biological perceptible modifications (virus proteins, antibodies) or symptoms. It also contains, for example, economic, psychological, and social changes resulting from the epidemic.

Transfer of some parts of the Tangible Trace occurs when a contagious person infects another individual (e.g., a COVID-19 patient coughing in the presence of others) or contaminates any entity (e.g., a COVID-19 contagious person deposits some parts—active viral material—of the Trace on a surface or an object). Epidemiology is concerned with these questions of transfer, as well as with the persistence of viral material of the Trace in different conditions (temperature, type of surface, etc.).

Illustrative Example 14 (Virus Infection) - Virology (Part 2)

Mr. A has been infected by a virus. The Event of interest is the infection itself; its duration typically varies between less than one minute (e.g., an infected person is coughing towards Mr. A) to a half an hour (e.g., Mr A. remains near an infected person with no visible symptoms). Mr. A's body delimits a Region and a corresponding Scene $\mathbb{S}$. The Tangible Trace is not limited to the virus proteins in his body. It comprises any perceptible change related to the infection. Intrinsic events amplify the virus within the body.

As the virus develops, symptoms become stronger and belong to the Tangible Trace too. As time goes on, antibodies are created as a body's natural response (intrinsic event) to the virus infection. After the person has fully recovered, the Tangible Trace might not contain virus proteins anymore, but still has antibodies whose presence represents a vestige of the infection (the original Event of interest).

or even a fact. Actually, these data are observed facets of the digital Tangible Trace with all the associated characteristics: conceptual, relative, practical, camouflaged, partially perceived, and dynamic. To deal with inherent uncertainty, digital forensic science requires a structured approach to evaluation of observations, the same as other forensic disciplines [23].

Second, digital forensic science allows comparison between data sources to discern detailed modifications resulting from an Event [24]. For example, comparison with a backup/snapshot reveals files or data that were added, removed, or changed. Furthermore, forensic analysis of incongruities in data structures can indicate that something was removed, and can sometimes find elements that were added (e.g., forged digital signature) or changed (e.g. substituted numbers). Although the ability to observe such modifications is compatible with the conceptual model presented in this work, it remains at the tangible level with all of the associated limitations and uncertainties.

More sophisticated modeling of computer systems such as finite state machines was proposed to determine the most likely cause of a particular missing or altered item [25]. By representing the state of a computer using sequences of observations, the current state of the computer can be compared with a theory of what occurred to compute the most probable event. This approach focuses on observable facets of the digital Tangible Trace and does not take into account facets of the Trace in the physical world, such as human interaction with input devices and sensors.

The Cyber-investigation Analysis Standard Expression (CASE) represents outputs of digital forensic tools as observable objects and facets, supporting precise and formal conceptualization that aligns with the model presented in this work.[12]

10.3. *Witness memory observed facets*

The formal model in this work can be applied to the personal memory of a witness of an Event.

During testimony, a witness might communicate parts of her memory about an Event of interest. The corresponding Trace in this

[12] caseontology.org.

context is located in the brain of the witness, mainly in her brain synapses. The Region for the Scene of Investigation is the volume delimited by the witness' brain. The Tangible Scene corresponds to her actual dynamic brain. The Abstract Scene consists of her hypothetical dynamic brain in an abstract World where the Event of interest would not have happened.

The personal memory of an Event of interest is a part of the difference between these two scenes; it belongs to the first component of the perceptible difference between the actual dynamic brain and the hypothetical one in the Abstract World.

With current technology, her personal memory—one facet of the Tangible Trace—cannot be observed precisely using external instruments, but is accessible through the witness herself. The witness is the observation instrument in this context and communicates her recollections.

The observation instrument (the witness herself) might be efficient or not, very faithful or unreliable. This influences the precision, as well as the quality and the completeness level of the observation of her personal memory. When asked different questions, the witness might provide differing accounts of what happened.

11. Scope of the model

The scope of the model is not limited to forensic science. Many other scientific disciplines examine vestiges of past events in an attempt to understand and describe former realities. Paleontology studies fossils in order to learn about ancient forms of life on earth. The Event of interest could be a dinosaur walking in a field. The fossilized dinosaur's footprint belongs to the Tangible Trace of the Event of interest. Astronomy studies signals from Events which have occurred billions of years ago. The Cosmic Microwave Background belongs to the Tangible Trace of the Big Bang. Gamma-ray bursts belong to the Tangible Traces of recurrent cosmological cataclysms. The light emitted by a star and observed by a telescope is part of the Tangible Trace of a nuclear reaction that happened sometimes millions of years ago. Dendrochronology observes tree rings—facets of Tangible Traces—in order to determine the exact age of a tree: Events of interest are related to yearly climate and atmospheric conditions. Geology, archeology, history also belong to sciences of the past which study Tangible Traces of past Events of interest.

Several modern technologies are based on the study of a Tangible Trace's facets of provoked known Events. Ultrasound technology creates an Event (generation of an ultrasound), then observes a facet of the Tangible Trace (the echo of the ultrasound) in order to compute some properties of a Scene of interest (e.g. within the body of a patient).

A medical practitioner's diagnosis is based on observation of symptoms (facets of a Tangible Trace) resulting from an alleged sickness (alleged Event). Testing a new drug or vaccine can also be analyzed in the light of the model.

The COVID-19 pandemic gives a very topical application of the model in this work. Table 2 represents the COVID-19 pandemic, whereas Table 3 represents an individual infection.

As already mentioned, virology and epidemiology offer interesting examples of Trace amplification. The COVID-19 pandemic raises the importance of a unified understanding of the Trace across scientific disciplines. Different facets of the COVID-19 pandemic cannot be treated in isolation: how to address the root causes of Coronavirus evolution, how to prevent death due to COVID-19, how to stop infection, how to curb propagation of contagion, how to minimize economic losses, how to maximize healthy behavior, and how to maintain civil society during a pandemic. Each scientific discipline sheds light on COVID-19. Virology focuses on the viral disease itself, as well as possible treatments for patients. Epidemiology studies how a virus spreads, how a vaccine or organizational measures can help control virus propagation in a population. Economics analyses the financial ramifications of different responses to a pandemic. Psychology examines people's behavior during a pandemic, including their reactions to COVID-19 risks and restrictions, financial and personal pressures. Sociology considers the complex interactions between people and their circumstances. Vast amounts of digital data are being collected and correlated to track individual infections, to enforce social safety measures, to observe trends in virus propagation, to give the sick more effective treatment, to develop a vaccine, to mitigate negative financial effects, to learn about people's behavior and opinions, and much more. Ultimately, a unified understanding of the various perceptible facets is needed to deal with a virus such as COVID-19; see Illustrative Examples 13 and 14.

12. Conclusions

The usual focus in forensic science on specialized technological developments to analyze one specific dimension of the Trace distracts us from its core and full nature, its properties, and how it works. Although the Trace is always partially perceived, greater understanding should be gained with a more general, formal study. This paper introduces a formalized model and associated definitions to support a more precise, unified understanding of the Trace across scientific disciplines. This model aims to stimulate more formalized study of the Trace as a diverse and complex entity, drive deeper understanding of the underlying processes, and gain further insights into the dynamics of the Trace.

Author statement

Both authors are equal contributors in all aspects of this work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Conflict of interest

The authors have no conflicts of interest related to this work.

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