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A common framework to situate digital and physical traces in time

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ABSTRACT

In this article, three main approaches to situate forensic traces in time were revisited under the prism of the Sydney Declaration and adapted to be applicable to a large range of physical and digital traces. The first approach is based on **time tags** which are time-based characteristics produced as the result of an activity at a specific time. They can either be directly related to time (i.e., time stamps) or indirectly (i.e., time indicators). While relatively straightforward, time tags require scientific knowledge to be correctly interpreted and to account for the risks of desynchronisation, anomalies and manipulation. The second approach is based on **time dynamics** and aim at measuring changes that occur as a function of time, such as caesium pulsation (i.e., on which international atomic time is based) or body cooling after death (i.e., from which time since death can be inferred). However, time dynamics phenomena are generally also influenced by other case-specific factors (e.g., environmental factors), and thus more difficult to reliably implement in practice. Finally, the third approach relies on **relative sequences**, using information unrelated to time, such as relative positions or dynamics of traces at the scene. As each approach has its potential and limitations, a combination of traces from different (both material and digital) sources and approaches is recommended to answer time questions in practice (When? How long? In which succession?) and enhance the reliability of the dating endeavours. It is strongly recommended to consider the principles of the Sydney Declaration when implementing or developing dating methods, as they point at potential issues that are often forgotten in forensic research and practice, such as uncertainties linked to the concept of trace, scene investigation, the asymmetry of time, the importance of context and the multiplicity of purposes. Future research should focus on improving the reliability of these dating approaches by combining and systematising their usage in investigative practice, as well as in broader intelligence processes.

1. Introduction

Temporal issues are omnipresent in forensic science [1]. As specified in principle 2 of the Sydney Declaration (SD), crime scene investigation and reconstruction are essential and challenging tasks [2]. The reconstruction of past events, such as crimes, necessitate to situate persons, objects and activities in time (and generally also in space). Typical time questions asked during investigations are:

– When was a person at a given location?
– How old is a person?
– How fast did a vehicule drive?
– When did an activity occur?
– How long did an activity last?
– Did an activity occur several time (how often)?
– In which succession did activities occur?

While not exhaustive, this list gives an overview of the main time questions related to absolute time (t), duration (Δt) and relative time ($t_1 \leq t_2$) inferences. Traces,[4] produced during the events of interests by the involved persons, objects and activities, are fundamental vectors of information for the investigation, including temporal information (principle 1 of SD) [2,3]. Thus, situating traces in time is of particular interest for forensic scientists [4,5]. However, it generally remains a relatively

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[4] While the term « trace » is still largely misunderstood in forensic science, it is recognised as an essential concept in forensic science (Roux et al., 2022). The trace is a remnant of past activities and presence. Traces need to be detected, recognised, analysed, and interpreted to reconstruct and understand the events of interests.

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complex endeavour in practice due to time asymetry (principle 4 of SD) [1,2,5]. The field of questioned documents has historically been a pioneer field for "dating" research; and approaches were documented and formalised relatively early [6–8]. Later, a general framework was proposed to situate forensic traces in time [5]. While the proposed approaches were supposedly applicable to all type of traces including digital traces, some inconsistencies were detected. For example, the so called "ageing" approach was not really applicable to digital media for dating purposes, and the "chronology" approach was too broad (also partly emcompassing the other approaches). Thus, it was necessary to revisit the previously introduced framework taking into account the increasing digitalisation of our society as the number of digital traces generated during any event of interest has, and continues to, exponentially increase [9]. Digital traces, similarly to physical documents, are fundamental vectors of temporal information thanks to all activities being recorded and timestamped within files and systems [10]. However, manipulation and anomalies of time related data have regularly been encountered in forensic cases, thus highlighting the need for a scientific approach to address dating questions, and the related uncertainties, both in the physical and digital environments (principles 3 and 5 of SD) [2,5,10–17]. After introducing useful concepts linked to the notion of time, this paper aims at revising and extending three previously proposed approaches [5] to situate both physical and digital traces in time under the prism of the SD principles. The approaches are illustrated through several real-life examples. Their limitations and potential are discussed in view of the multi-dimentional purposes of traces within case specific contexts (principles 6 and 7 of SD) [2,5]. This work aims to help practioners in their endeavour to situate traces, objects, persons and activities in time, and highlights how the SD and associated principles are omnipresent in any forensic endeavour.

2. Time

While time remains difficult to define, several temporal concepts can be described and are valuable to situate traces in time. First, time is asymetric (see principle 4 of SD) [1,2]; it flows and does not stop, leading to events and existences unfolding irreversibly and in succession. Thus, investigated activities largely remain in the past and need to be reconstructed using investigative inferences analogous to reasoning used in the historical and medical sciences (see principle 3 of SD) [2,18,19]. The notion of succession, linked to the notions of asymetry as well as simultaneity, indicate the relative nature of time, as events occur either before, at the same time or after other events of interest ($t_1 \geq t_2$). However, time can also be measured in absolute units, as a point in time t or as a duration Δt (in years, days, hours, minutes, seconds…). Time can be viewed linearly (i.e., asymetric succession) or cyclically (i.e., repetitive yearly, weekly or seasonal pattern) [4]. Thus, time appears in different perceptible forms in the physical world that can be translated digitally (see Fig. 1). These concepts are at the basis of the dating framework presented in the next sections. While nowadays we mainly use digitally translated time to give rhythm to our lives, the concept of time is based on physically measured time dynamics such as the oscillation of crystal within electronic devices [20] or caesium pulsation [21]. The latter is used to obtain high precision international standards such as Atomic International Time (TAI) and Coordinated Universal Time (UTC). Both standards are maintained through "a combination of data from about 450 at. clocks operated by more than 80 timing centres" [22].[5]

3. Dating

Based on the concepts introduced in the previous section, three main dating approaches can be described and used, often in combination, to situate traces in time: time tags, time dynamics and relative sequences. These approaches will be described in the next sections. Examples of application, as well as limitations, will also be discussed.

3.1. Time tags

The first approach is based on time-based characteristics, so called time tags, that are produced as the result of an activity at the **time t** (see principle 1 of SD [2]). It was first defined in the field of questioned documents, and essentially referred to time related information added to documents and inks to help in the detection of document fraud [6,8]. In practice, two main types of time tags can be distinguished:

- Time stamps designed in the form of **voluntary, sometimes official, temporal data** such as a postal stamp or a digital timestamp.[6] A time stamp can be defined as the explicit recording of the time of occurrence of a particular event whether in a physical or digital environment. Time stamps are recorded in absolute units according to different conventions and precision. For example, a date (13/01/2023), a date and hour (13/01/2023 at 9:46 AM) or the number of seconds since the 01/01/1970 (1673599560).[7]
- Time indicators in the form of **content that is indirectly related to time**. While time stamps are explicit and voluntary records of the time of occurrence of an activity, traces can also contain implicit time related information. Such time tags initially have no dating purpose and thus, require knowledge to be associated with a moment in time. For example, certain characteristics can be linked to records, including the time of production. This can apply to a specific object, such as the serial number of a firearm, or of a type of objects, like the sole pattern of shoes. It can also refer to the time of release of a specific software or hardware at the source of digital traces.[8]

Time tags, and more particularly time stamps, are frequently used in investigations, whether by forensic scientists or police investigators [5]. Thus, it is very important to discuss the requirements and limitations associated with the use of time tags (see principles 5 and 7 of SD [2]). They range from (de)synchronisation to manipulation of the time stamps and related data. While not specifically discussed in this paper, the investigation can also pollute or erase the relevant traces [3]. Thus, particular care should be taken, even in digital environments, to preserve the traces.

Knowledge about the precision (t ± standard deviation) and accuracy (t ± systematic bias) of a time tagging system is needed to correctly interpret and compare temporal information. Except for TAI, a precision between devices below the nano-second remains difficult to achieve [23]. Additionally, systematic bias can occur when systems are settled in different time zones. Coordinated universal time (UTC) offsets are geographically settled, for example as UTC+1 in UK and UTC+12 in New Zealand approximately from March till October, as it also depends on daylight saving time (DST)[9] settings. Nowadays, most internal clocks of on-line systems are continuously updated and synchronised in reference to TAI (using, for example, network time protocols (NTP) or Global Navigation Satellite Systems (GNSS) signals (such as Global Positioning Systems (GPS)). However, a device can still be subject to diverse conditions that may impact the accuracy of time data such as delays in the transfer, temporary loss of signals (e.g., when a device is switched-off), failing batteries, or manipulation of clocks and timestamps [24,25]. Thus, the reliability of temporal information must always be questioned,

[5] https://webtai.bipm.org/database/ (last access: October 2023)

[6] Time stamps is used in two words in accordance to the Oxford dictionary spelling to define all kind of stamps (material or digital), while timestamps is used only to discuss digital stamps

[7] https://unixtimeconverter.net/ (last access: October 2023)

[8] Implicit in the meaning: suggested but not directly expressed.

[9] https://www.timeanddate.com/time/map/ (last access: October 2023)

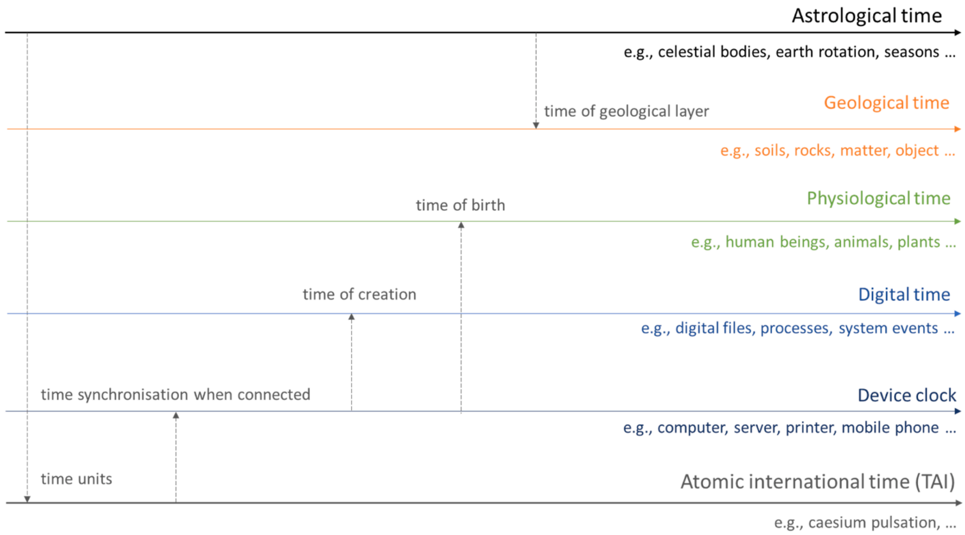

Fig. 1. Astrological phenomena rhythm our time and are at the basis of units of measurements (e.g., hours, days, months, years). Time is measured physically, for example using atomic clocks (e.g., Caesium pulsation) and translated digitally for international synchronisation (e.g., using the Network Time Protocol (NTP)). While mechanical watches are still used, digital devices (e.g., watches, mobiles phones, computers) mainly help us keep track of time nowadays. Many other phenomena are used to measure or feel the passage of time such as physiology (e.g., growth and ageing of living organisms) or geology (e.g., evolution of earth physical structure).

controlled and when possible calibrated. Slight desynchronisation remain problematic when comparing high amount of time data from different sources [26,27].

Some time stamps are known by the users (e.g., postal stamp, date on a physical document, creation date and time of a digital file), others are more hidden from the users and require additional knowledge to be extracted and interpreted (e.g., laser printer code or micro-impression inserted in physical documents, GPS date and time recorded in the exchangeable image file format (EXIF) metadata of a picture or time-stamps in system journals to log file activities[10]). The former can more readily be modified (for legitimate or forgery purposes) as they generally are observable from and explicit to most users. Whereas the latter are *latent*[11] and thus, less at risk of being tampered with, but also potentially more difficult to extract and interpret. For example, a latent security laser printer code is a pattern of toner points indicating, among other information, the time of printing. However, extracting temporal information from such a code requires optical instrumentation and a translation library [28]. Similarly, the extraction of all the EXIF metadata also requires specific tools such as Exiftool[12] (see example in Table 1). While time is usually translated by the computer systems in known units (date, hours, minutes, seconds), it can also be expressed using other conventions that need to be translated in understandable (and comparable) units. Typically, computer systems store timestamps as numbers that represent an interval of time elapsed since a fixed date and time, known as an epoch. For example, Windows operating systems usually stores timestamps as the number of 100 nanoseconds intervals since the 1st of January 1601 [17]. Time indicators are also less known to users, and thus generally less at risk of being tampered with. They can be useful to corroborate the information conveyed by time stamps. For example, if an object represented on a picture was fabricated after the time stamps given by the metadata, the reliability of the latter should be questioned. In such cases, the object is a time indicator (e.g., a Tesla Roadster car is indicative of a time after its first production date in 2008).

[10] System journals such as the $USNjrnl or the $LogFile on Windows.

[11] *Latent* in the meaning: *hidden, not apparent.*

[12] https://exiftool.org/ (last access: October 2023)

Table 1
Time stamps extracted from the file system and EXIF metadata of two image files: both files represent the same photography and were saved on a computer from a mobile phone on the 16th of October 2023. The first image file was saved by the camera of the mobile device (taken on the 4th of September 2023), while the second file was created by WhatsApp on the 16th of October 2023 (at 21:22) when the photography was sent to a recipient. Both files were accessed after being saved on the computer. Both file names also contain a date. However, the EXIF system metadata were lost when the file was sent via WhatsApp. The original creation date and time of both files were updated when saved, while the WhatsApp file name only contains a date.

Source	Type	Camera file
File system metadata	File Name	20230904_ 094841.jpg
	File Creation Date / Time	16.10.2023 21:29:51+02:00
	File Modification Date / Time	04.09.2023 16:38:17+02:00
	File Access Date / Time	16.10.2023 21:31:45+02:00
EXIF metadata	Modify Date	04.09.2023 09:48:41
	Date Time Original	04.09.2023 09:48:41
	Create Date	04.09.2023 09:48:41

As explained above, time stamps known by the users can be relatively easily falsified, either directly[13] or by modifying the device internal clock. However, such manipulations and other anomalies can usually be detected by combining different types and sources of time related information [10,17,29]. For example, Kaart and Laraghy [16] described a case study where externally generated timestamps stored in the body of SMS messages sent by the mobile operator of an Android device (e.g., notification of missed calls or voicemail messages) were used in combination with their file system metadata to determine the clock settings of the device at the time of their creation. They were able to determine that over the period relevant to the investigation, the clock was set to a

[13] A rapid search on the internet informs the users how to modify the time-stamps of a file.

Table 2
Examples of time tags to illustrate the time stamps and time related dating approaches.

TIME TAGS	
Time stamps *characteristics with explicit dating purpose,* *can be visible or hidden*	Time indicators *characteristics indirectly related to time,* *implicit and generally requiring translation*
Examples - Time of creation, modification, deletion, access of a file - Time of events recorded in a log file - Time of fire alarm triggering - Postal stamp on an envelope - Date of birth of a person - Date of issue or expiry printed on a passport - Printed or manuscript date on a receipt - Date and time on a train or bus ticket - Production and expiry date on packaging - Time of last heartbeat measured by a connected watch - Time of a GPS positioning - Time indicated in a text message (e.g., let's meet at 1pm for lunch) - Latent code printed on a document - Ink tag indicating the year of production	***Examples*** - New compounds added to fabrication processes (e.g., optical brighteners in paper since 1950s) - Fabrication period of a specific sole pattern - Fabrication period of a watermark or logo - Witness statement (e.g., I met the person on my way to work) - Image content (e.g., an electric car model marketed since 2008) - Time of wound associated with medical records (e.g., scar on a finger) - Date of release of a software / hardware at the source of traces - New release of or features added to an operating system version

different time zone than the current configuration. Furthermore, some time stamps may be more difficult to alter than others. This is the case for example on Windows where a file generally has at least eight timestamps [30]. Among these, four timestamps (stored within the $STANDARD_INFORMATION attribute[14]) are visible to the user and updated by any file operation such as accessing or modifying a file. These timestamps can be relatively easily tampered with, using a terminal or any specialised tools available on-line such as Timestomp. In contrast, the four other timestamps (stored within the $FILE_NAME attribute) are latent and altering them necessitates advanced forgery tools [31]. Similarly, the visible dates on a paper document can relatively easily be falsified when creating the document or later by erasure and modification that can be searched for using optical means, while latent code or watermarks may be significantly more difficult to alter [28].

However, anomalies or inconsistencies in the comparison of temporal data are not a proof of manipulation and can be fostered by a lack of precision or accuracy, as well as normal system activities and modifications. Digital traces, like physical traces, are the results of one-off events (see definition of forensic science proposed in SD [2]) and, as such, present a variety of characteristics due to the particular source and environment characteristics (e.g., difference between devices) as well as the transfer processes (e.g., copy-pasting, backup process, file transfer…). This underlines the importance of considering uncertainties in dating (as in all forensic) endeavours, as indicated by principle 5 of the SD [2].

Finally, while digital time stamps are omnipresent in our lives, we are still using non-digital time stamps in our daily activities, as well as in investigations (e.g., people inferring time from mechanical devices).[15] Such stamps can be written on paper document or reconstructed from witness statements (i.e., "I consulted my watch when it happened, and it was 8 o'clock"). More uncertainty is generally attached to such temporal information (e.g., memory distortion and loss, as well as potential lies). However, they remain an important source of temporal information among others and should not be entirely neglected (see principle 1 of SD [2,3]).

3.1.1. Examples

In a digital environment, the time of most, if not all activities is recorded within files and systems: creation, modification, accessing, deleting of files, log of activities, sending messages, installation of software, back-ups, calls, alarms, GNSS positions, heart beats or steps (see Table 2). Other illustrations of time stamps are train tickets, postal stamps and purchase receipts. For example, receipts from food shops can be used to reconstruct the time of the last activities of a deceased person, and search for other traces around the time of shopping (e.g., CCTV images). The serial numbers stamped on objects during their fabrication often contain an explicit date. This is also the case for identity documents (e.g., passports and driving licenses) that generally contain several dates (e.g., date of issue, date of expiration, date of birth of card's holder). The automatic naming of digital images and scanned documents nowadays often includes the date, and sometimes also the time, of creation (see Table 1).

The following example is more anectodical but can still be useful in investigation. Specific compounds were added to time stamp inks during production in the US during the past century [6]. Every year, different compounds were added to the pens introduced on the market. The compounds were transferred from the pen (i.e., source object) to the paper while writing. The analysis of the produced ink writings (i.e., traces) allowed the characterisation of the contained compounds, and thanks to a library, gave information on the year of first introduction of the given pen on the market. The selected compounds (for example rare earth organometallic compounds) were stable within the ink cartridge as well as within the trace. This so-called tagging program started in the mid-1970 s, but unfortunately had to stop for different reasons including difficulties to find adequate compounds to continuously tag inks over the years [32]. It also required a detection method (x-ray fluorescence) and a translation library (in which the added compound and characteristics were associated to a year of production). Such tagging was intentionally developed to time stamp documents but remained mainly unknown from the users. Forgery of questioned document is a recurrent issue and thus, it fostered the development of many latent time stamping approaches (such as inclusion of latent watermarked or microprinting including dates in the paper) to help in the authentication process. Similar (time) stamps have been included in toners, security inks and documents for example.

While less used in investigation, time indicators can be of particular use to detect forgeries due to their implicit character (see Table 2). A famous example is linked to industrial modifications over time. Optical brighteners were introduced in paper production in the 1950 s. While common knowledge at the time for document experts and paper fabricants, such information was less known by the general population and

[14] On Windows, a file and its metadata are stored in a set of data structures, called attributes. Timestamps associated with a file are stored in two different attributes named $STANDARD_INFORMATION and $FILE_NAME.

[15] While connected devices use is spreading, crime scene investigations can take place in remote locations where no network is available. Digital devices can also be out of battery or service. And although, scene investigation documentation is nowadays partly digitally captured (e.g., photographs), some of it usually remain handwritten.

Table 3
Examples of time dynamics and associated dating application. Some of the main influence factors apart from time are also listed (non-exhaustively).

TIME DYNAMICS		
Dynamics phenomena	*Proposed applications*	*Main influence factors*
- Body cooling [58]	Time since death	Body and room temperature
- Cicatrisation (healing) [59]	Time since wound was inflicted	Person dependent physiology and health
- Circadian markers cycle [54]	Time of day	Person diurnal and nocturnal habits
- Telomere length [46]	Age of a person	Between person variations
- Ossification processes [60]	Person being over majority	Sociocultural criteria
- Physical appearance (ageing) [61]	Age of a person (biometrics)	Illness, cosmetics, and artefacts
- Haemoglobin oxidation [14]	Bloodstain age	Stain thickness and exposure to light
- Lipid degradation [35]	Fingermark age	Donor lipid secretion composition
- Solvent loss [47]	Ink entry age	Ink initial composition
- Volatile residue diffusion [13]	Time since discharge	Firearm and ammunition type
- Fungi growth [39]	Vegetable metamorphosis	Exposure to light and humidity
- Leaf presence and colouring on a tree	Seasonal pattern	Weather fluctuations
- Shadow length and orientation [56]	Celestial bodies movement	Terrestrial coordinates
- Caesium frequency [21]	Atomic international time	Synchronisation
- Crystal oscillation [20]	Device system clocks	Aging and temperature
- Video image recording (# per seconds) [57]	Duration of an activity on the image(s)	Software
- Automatic save and backups	Time of a scheduled action on a device	Device or action switch-off
- Phone call duration	Time interval of a (digital) action	System implementation

became partly forgotten over the years. The presence of optical brighteners in the paper of the discovered *Hitler's diaries* indicated an anachronism compared to the dates indicated on the documents [33]. The diaries were supposedly written by Hitler during his lifetime, thus, before his death on the 30th of April 1945. While such implicit time related content is not very precise and indicates only a broad time interval (in this example, the presence of the optical brighteners indicated that the paper was produced after the 1950 s), it can still be very useful in some instances. Nonetheless, it requires a good knowledge of the production of the involved objects and ideally, libraries recording all composition changes over time [6,8]. While this can theoretically be applied for all kind of object and even persons (e.g., lifetime of a given pattern under a shoe sole, appearance of a scar on a palm print), in practice such examples remain limited outside the questioned document field, because it requires important resources to acquire information allowing to associate time with the data for a relatively limited feasibility in practice (partly due to fabrication confidentiality and globalisation of the markets).

However, comparison of the time information conveyed by different time tags can be used to detect anomalies. For example, a trace from a person cannot have been transferred on a scene before they were born, or while they were held in a prison cell. DNA or fingermarks found on a scene of investigation leading to the identification of the person at the source of the traces can lead to a birth date, as well as other temporal information (i.e., time of employment or incarceration). For example, fingermarks identified on crime scene were transferred in some instances during a previous event, unrelated to the investigated crime, indicating a good persistence of the trace characteristics over the years in some conditions (for example on windows protected from environmental conditions) [34,35]. Similarly, a digital trace created by a particular device cannot have been produced before the device was developed. For example, if the EXIF metadata of a picture indicates the picture was taken with an iPhone XS, the timestamp indicating when the picture was taken could not be at an earlier date and time than the first iPhone XS model release.

3.2. Time dynamics

The second dating approach is based on characteristics that change as a function of time, so called time dynamics [7]. For example, the observation of the movement of celestial bodies such as the earth rotation on its axis relative to the sun (e.g., ~24 hours) or its revolution in orbit around the sun (e.g., ~356 days) are at the basis of our time units. While the sundial was one of the first measurement instruments of time, the clepsydra, hourglass or candles were invented to measure relative durations. Nowadays, time is measured with high precision using atomic clocks, for example through the frequency of Caesium [21]. These phenomena were chosen, and to some extent calibrated, to be essentially time dependent. Following the same logic, other changes driven by time were considered for dating purpose in archaeology and forensic science such as carbon 14 decay [36,37] or physiological changes after death [11].

As all matters are subjected to changes (whether cyclic such as seasonal patterns or linear such as plant growth or decay), many phenomena have been proposed in forensic science to situate traces [12,14], objects [8], human beings and other living organisms [38,39] as well as events [11,13] in time (see Table 3). However, most phenomena are also influenced in real life by a multitude of factors other than time (such as environmental conditions), thus considerably complexifying most dating endeavours based on time dynamics (see principles 5 and 7 of SD [2]).

This approach is based on time asymmetry (principle 4 [2]) and the fact that when an event occurs at time t_1 (e.g., when a person dies or a trace is transferred), different processes take place over time Δt (e.g., body temperature decreases [11], and bloodstains dry and fade [40]). If the process dynamics are plotted as a function of time (Fig. 2), then the time of transfer (t_1) can theoretically be inferred through abductive reasoning from the characteristic measured at the time of examination t_e

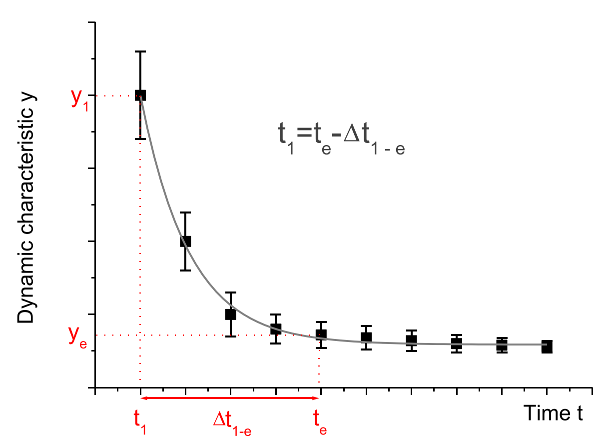

Fig. 2. Hypothetical time dynamics process following an exponential decay. An activity of interest occurred at time t_1 (e.g., bleeding). The analysis of the trace (e.g., bloodstain) at time t_e, resulting in the value y_e, theoretically allows inference of y_1, and thus t_1, from the decay function.

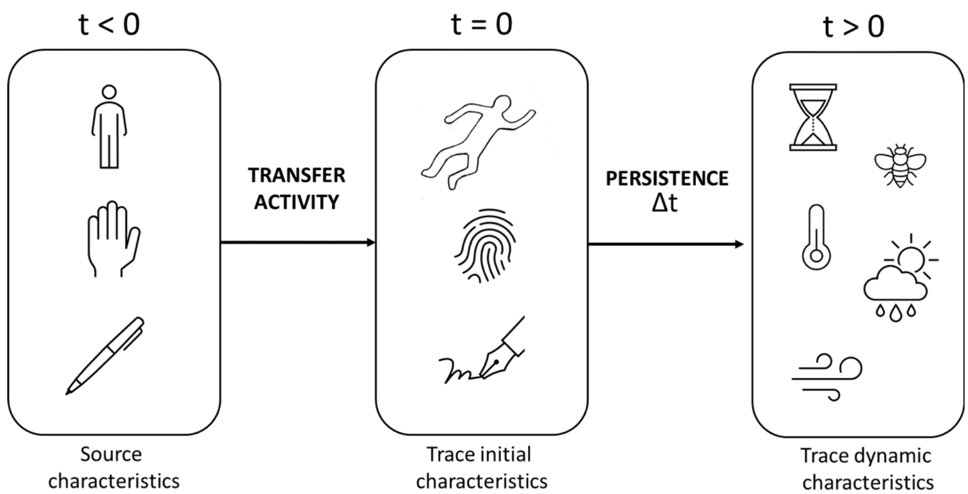

Fig. 3. Source persons and objects possess different characteristics (e.g., health status, secretions contents, ink composition and pen characteristics). During the activity of interest (e.g., death, contact between a finger and a surface, writing), initial characteristics are produced and transferred to the scene. These will be influenced by the event specificities (e.g., cause of death, reception substrate, transfer pressure, duration, and angle of contact). Over time, some characteristics will be lost or modified until they can be measured. Apart from time, the dynamics are generally also influenced by other factors (e.g., environmental conditions).

(e.g., body temperature or haemoglobin fraction in a bloodstain) (see principle 3 of SD [2]).

An ideal time dynamics characteristic should [12]:

- Be present and easily analysable in most cases,
- Undergo a reproducible and measurable modification over time,
- Be as little as possible influenced by other factors than time.

The time span of measurable dynamics should be known (e.g., seconds, days, months, years). For example, body temperature cooling will work within a few hours [41], whereas insect colonisation will occur over several weeks [42]. Reliable time estimation requires to know the error of measurement. However, the main variation often comes from the specimen itself and its related dynamics characteristics, which are also influenced by many other factors in addition to time (see principles 5 and 7 of SD) [2,5]. These influence factors can be classified in three main groups (Fig. 3):

Fig. 4. In this case, the time of the photography was in question. As the coordinates were known, the shadow orientation allowed to infer the time of the day (~ 3 pm), while the shadow length indicated the time of year (either February or November). As the year of the photography was also known (and not contested), the fact that no leaf was on the tree (above left) indicated that the picture was taken in February rather than November. Time tags and related information were also used to precise the time frame. No merchandise was displayed outside the shop as usual on opening days (below right), indicating a Sunday or holiday. The weather recorded in February finally narrowed down the possibilities to a specific Sunday.

- before the event $t < 0$ (e.g., source object or person related characteristics),
- during the event $t = 0$ (e.g., transfer or event related characteristics),
- and after the event $t > 0$ (e.g., environment and subsequent activities related characteristics).

While some processes are essentially governed by time (e.g., Caesium pulsation), many are influenced at least in equal measure (and sometimes even more) by other factors in the uncontrolled environment of real cases. When those factors are known (e.g., type of substrate on which a trace is detected) or can be inferred from the investigation (e.g., cause of death or weather records), time dynamics specific to the investigated case can be modelled through inductive reasoning (see principle 3 of SD [2]). However, in many instances some influence factors remain undetermined (e.g., ink pen used to sign a document, indoor long-term storage conditions). Thus, the dating potential of this approach is often limited in practice and in many instances dating remains unfeasible [35,43–46]. While this approach has mainly been proposed for physical traces, digital traces (e.g., video image recording) may be less influenced by external factors. However, the source software and hardware may still significantly influence the production and storage of traces.

3.2.1. *Examples*

Many dating methods based on time dynamics have been proposed in forensic science, predominantly to date physical traces (Table 3). Few are routinely applicable in practice either due to the lack of available knowledge about the dynamics (e.g., insufficient resources to build case-specific time dynamics models) or due to lack of reliability of the models (e.g., unknown influence factors in practice). Possibilities and limitations will be illustrated through a few examples.

Time since death interval, for example, can be inferred from time dynamics characteristics such as body cooling, post-mortem lividities, rigor mortis, supravital reagibility of skeletal muscle, putrefaction, metabolics, autolysis, RNA degradation, radiocarbon dating or colonisation by insects [11]. However, only a few processes, such as body cooling, have been extensively and systematically researched including field studies allowing for its routine application within error margins due to known (and potentially unknown) influence factors. According to Burkhard [11], other methods (e.g., assessment of supravital reactions, rigor mortis, and postmortem lividity) are mainly used to increase the precision of time since death estimation. Thus, the development and implementation of new approaches require long-term systematic

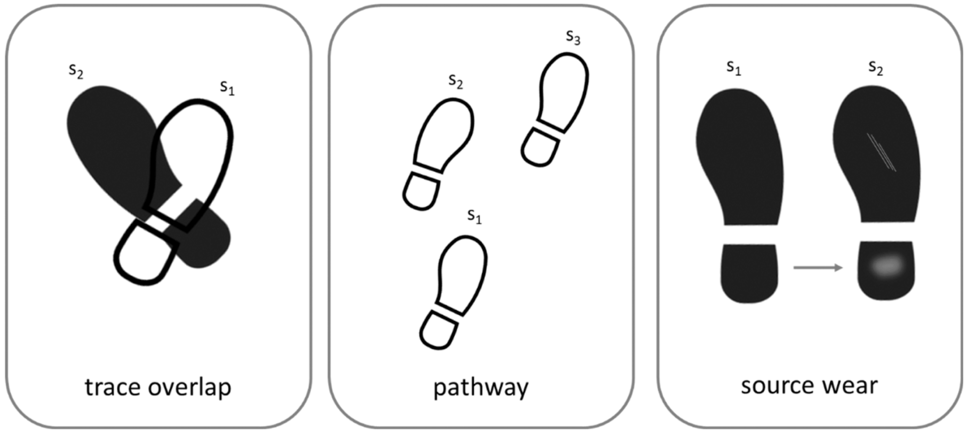

Fig. 5. Examples of different type of relative sequence information that can be extracted from trace characteristics (e.g., relative position, sole wear). These are linked to activity (i.e., walking) rather than time. Comparing the characteristics between several traces allows ordering them in sequence relative to each other (e.g., sole marks overlapping and/or indicating a pathway). Though rarely useful in practice, signs of increasing wear may also indicate a chronology between related cases.

studies. Even then, uncertainties will always be attached to the time since death estimation, mainly due to the (largely unknown and inferred from the investigation) case specific factors (e.g., health status,[16] body displacement, weather conditions, sudden temperature change[17]). The further away from the event the estimation is (large Δt), the larger the uncertainties. In practice, other approaches are often used in combination with time dynamics such as time stamps (see Table 2, for example: last digital action, last seen, last position of mobile phone…). Thus, very resources consuming methods, such as entomology are mainly available in larger laboratories, and applied to cases in which other traces are unreliable or inexistant. Burkhard states that [11]: "The best we can achieve is a reasoned guess by taking into account all known factors (page 181–182)." This highlights the limitations of such approaches.

Time dynamics phenomena have also been proposed for the dating of questioned documents, particularly for ink writings on paper substrate [47]. Several dynamics processes were proposed such as solvent loss, dye and pigments fading, ion migration or resins polymerisation. Only solvent loss has been found reliable enough for application in practice and mainly focused on one compound, phenoxyethanol, found in approximately 80% of the ballpoint pen inks [48,49]. As the loss is largely influenced by the ink's initial composition (and it can rarely be inferred which pen was used), models were built for large ink populations limiting the feasibility of the approach in practice [50,51]. Some inks contain no to very little phenoxyethanol, or loose it very quickly once apposed on paper. Thus, it is mainly possible to evaluate if an ink entry was recently apposed on a document (i.e., less than a few days or weeks ago). The storage conditions should also be known, as extreme conditions such as storage in a plastic folder or in a cold environment considerably slow down the loss dynamics. Comparable limitations were observed for dating models based on the time dynamics of bloodstains, fingermarks, gunshot residues, human beings, and wounds [13,14,35,46,52,53].

Cyclic phenomena were also proposed to situate traces and events in time, such as circadian markers, vegetable seasonal pattern or the length and orientation of shadows (see Table 3). However, circadian markers (e.g., production of cortisol and melatonin) are influenced by the lifestyle of people (e.g., circadian rhythms, consumption of substances containing the targeted hormones, exposure to light or stress) [54], and seasonal plant pattern (e.g., flowering) is usually influenced by climatic variations [55]. On the other hand, shadows length and orientation are mainly influenced by the time and exact coordinates of objects and people [56] (see example in Fig. 4).

Digital time dynamics, such as number of frame per seconds, were also used to situate particular events in time [57]. However, less time dynamics digital examples exist and those are usually less influenced by external factors apart from slight desynchronisation. Thus, digital examples such as video image recording, regularly scheduled actions such as back-ups and device system clocks generally have more precision and thus, higher potential to situate traces in time. Digital time dynamics may also be useful to detect possible time anomalies. For example, should a system's clock synchronise every 9 hours, any deviation in the regular time frame between these synchronisations (due to a clock drifting or an active clock manipulation) could be indicative of an anomaly. Other dynamic phenomena related to the rate of activity rather than time have more digital applications. They are classified and developed in the next approach.

3.3. Relative sequences

The third dating approach is based on relative sequencing based on trace characteristics unrelated to time [5]. Following the principle of unity of time, place and action [5], when traces bring no (or unreliable) information about time, inference must mainly rely on relative location (i.e., position) and action (i.e., dynamics). Indeed, traces can help reconstruct the chronology of events of interest without knowledge about the time at which they were created (see principles 2 and 3 of SD [2]). This typically is the case of sole marks location overlapping or indicating a pathway (see Fig. 5). On the other hand, usage creates dynamics characteristics that can also be relatively sequenced. For example, the appearance of wear marks on shoe soles can theoretically be used to sequence a series of cases in which sole marks from the same source are detected (Fig. 5).

It was suggested that this approach followed the same principles than stratigraphy, used in geology and archaeology to sequence soil strata [62,63]. For example, stratigraphy allowed to infer the time of disappearance of the dinosaurs as traces related to them (e.g., bones and

[16] For example, a person suffering from a fever at the time of death will have a higher initial body temperature.

[17] For example, when a body is discovered in a closed environment, it is not rare that first responders open a window to reduce unpleasant odours, thus unfortunately also changing the indoor temperature.

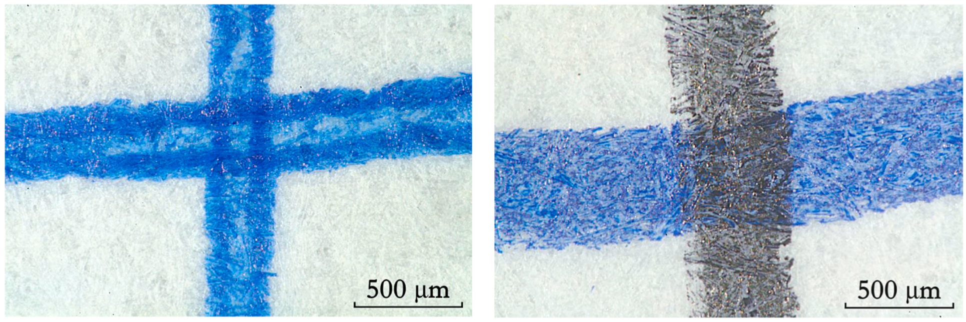

Fig. 6. Example of ink lines overlapping that cannot be reliably sequenced. The horizontal line was made first for the gel pen crossing (left), while the vertical black line was written first for the ballpoint pen crossings (right). These pictures were kindly provided by Dr. Ka-Man Pun.

Fig. 7. The sole marks detected on the soil of an appartement allowed to reconstruct the chronologies of events. Two persons entered through the window of the living room, one person (blue marks) went to check that the entry was closed, while the second person (pink marks) went to the bedroom. While looking for goods to steal, he was surprised by the inhabitant waking up. He shot her in the head and both authors left through the bedroom windows. The schematic representation has been reproduced from [67].

fossils) could only be found up to a certain sediment layer linked to the end of the Cretaceous Period, the so-called C-T (or C-Pg) boundary.[18] High amounts of iridium were found in this boundary supporting the hypothesis that dinosaurs disappeared following a meteorite impact on earth [64]. Similarly in forensic science, if traces can be associated with different "layers", their sequence of apposition can be determined through abductive reasoning (see principle 3 of SD [2]). This may seem straightforward when traces are at least partly overlapping. However, the determination of the sequence can be ambiguous (see principle 5 of SD [2]), for example when the first trace is apposed with much more pressure than the second. In such cases, the second trace's pattern may be invisible at the crossing giving the misleading appearance that it is below [65]. Similarly, overlapping traces may have undifferentiable characteristics making it impossible to determine which trace was deposited first (see ink line crossing example in Fig. 6). This approach can also be applied to traces that do not physically overlap, through feature comparison between traces (e.g., relative position, wear), indicating for example a sequence of creation (see examples in Figs. 7–9).

Stratigraphy also inspired relative sequencing in the digital environment and was proposed to infer sequence of files creation or deletion when metadata are missing or questioned [62]. As defined by Casey [62], digital stratigraphy is an approach that leverages the knowledge of file systems and the functioning of their allocation algorithms. Depending on the file allocation strategy, the logical position of files on a storage media may be used to infer the creation time of a file or to reconstruct activities. For example, a file allocated using the next fit strategy at a time t_1 will usually be positioned at a lower address on the storage media than a file created at time t_2, where $t_1 < t_2$. However, many file systems may operate under different file allocation strategies that may not be as predictable, thus limiting their utility to infer sequences of events (e.g., best fit strategy). Moreover, file systems allocation algorithms may deviate from their usual behaviour under certain conditions (e.g., fullness of the media storage) [62,66].

3.3.1. Examples

Examples can be differentiated based on the characteristics that are relatively sequenced such as location (i.e., relative position) or action (i.e., relative dynamics) (see Table 4):

3.3.1.1. Relative position. The relative position and overlapping of physical traces can help reconstruct the chronology of events. A typical example are latent sole marks indicating entry and exit ways, as well as

[18] C-T stands for Cretaceous-Tertiary. The Tertiary period was later renamed the Paleogene (Pg).

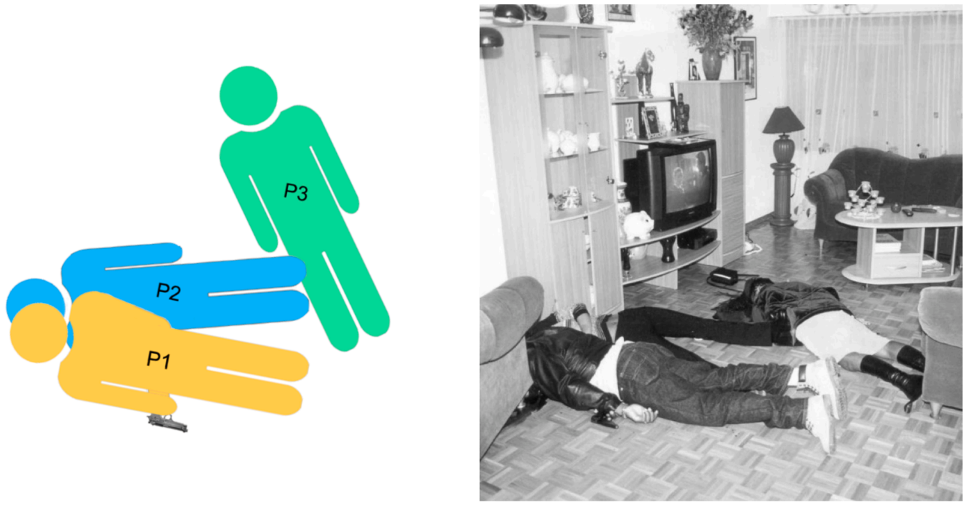

Fig. 8. In this case example, three persons were shot in the head (P1, P2 and P3). P1 was holding a firearm and was lying partially above P2, while the foot of P2 was partially on the coat of P3. The chronology of event was mainly reconstructed based on the relative sequencing of bullet holes and the three bodies' relative positions (see details in Section 3.2). It was inferred that P3 was shot first by P1, who killed then P2 shortly before killing himself.

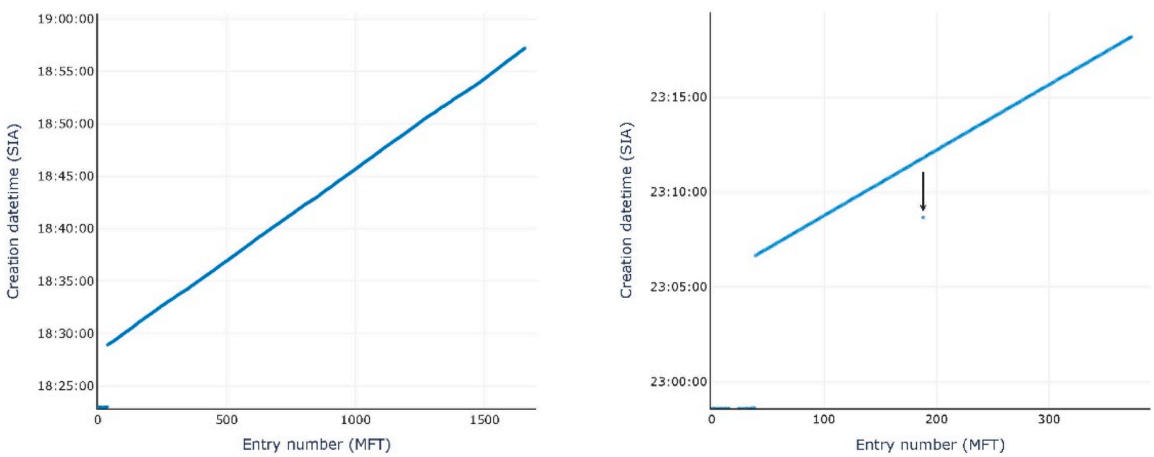

Fig. 9. Sequence of creation of timestamps obtained from the $STANDARD_INFORMATION attribute (SIA) as a function of plot of entry numbers allocation on two disk images (virtual hard disks [76]) where: (left) files of the same size where created until no space was left on the disk, and (right) same experiment with one file being backdated (using the command line). As illustrated on the left, in a situation where entries are allocated for the first time, the relative sequence of file creation can be inferred (independently from the timetsamps). In that case where one file creation timestamp was manipulated (on the right), the backdated file is detected because the relative sequence is not respected in comparison to its surrounding neighbours.

pathways within premises (see example in Fig. 7) [67]. The relative sequence of relevant traces found alongside can be inferred from the reconstructed pathway by association.

The relative sequencing of physically overlapping traces has also been researched for example for sole marks on blood, fingermarks over ink writings and ink writings over printed latent codes [67–69]. Due to the limitations of such methods, tests on known samples should systematically be carried out, as well as full validation on realistic specimens before practical implementation (i.e., including blind testing). An example was reported for paintings overlapping on canvas. Indeed, it is common to paint several subjects on the same canvas when the first attempt fails or to save the cost of the material. An example was reported by the Fine Arts Experts Institute in Geneva.[19] They revealed by reflectography the presence of a tractor painted under a nude attributed to the artist Albert Marquet and dated 1912. The type of tractor's tyres was apparently introduced on the market after 1930 revealing an anachronism by combining the relative sequences and time tags approaches.

The example of stabbing wound cutting through several layer of clothing and skin as well as bullet entry and exit holes used to reconstruct projectiles trajectories are typical examples of relative position sequencing. Kind reported a case in which a hospital doctor reported the presence of three stab wounds in an examined victim [70]. However, the reconstruction showed that only one stab had provoked these marks quasi-simultaneously but still in relative sequence: entry and exit wound in the arm, and entry in the side of the body under the arm. The holes in the different layer of clothing examined by the forensic scientist confirmed the hypothesis that only one knife stab event had occurred. In a previously reported case [71], the lifeless bodies of three person were found in the living room of an apartment. The three persons were shot in the head. Two bodies partially overlapped (P1 and P2), while the foot of P1 was on the coat of a third body (P3) (see Fig. 10). This supported the hypothesis that P2 fell before or at the same time as P1. P1 was holding a small calibre firearm in his right hand placed under his body, while P2

[19] https://artdaily.cc/news/73562/Fine-Arts-Experts-Institute–Lab-sleuths-in-Geneva-help-art-world-uncover-fakes (last access: October 2023)

Table 4
Examples of relative sequencing based on position and dynamic characteristics.

RELATIVE SEQUENCING	
Based on position	*Based on dynamic characteristics*
- Sole marks overlapping - Sole marks indicating a pathway - Writing overlapping on a document - Paintings overlapping on canvas - Wound bullet entrance and exit holes - Stabbing wound sequence of penetration - Marks imprinted in blood - Geological stratigraphy	- Relative quantity of volatile gunshot residue - Relative haemoglobin fraction in bloodstains - Sole wear marks due to usage - Apparition of a scar on a fingermark - Exponential loss of particulate matter (e.g., fibre persistence) - File name incrementation - Message numbers - Entry numbers (e.g., in the MFT) - Web history - Serial numbers - Logical position on a hard drive (next available) - Sequence related content of images (e.g., a person pathway) - Sequence related text or voice messages (e.g., mention of an action done before or after another)

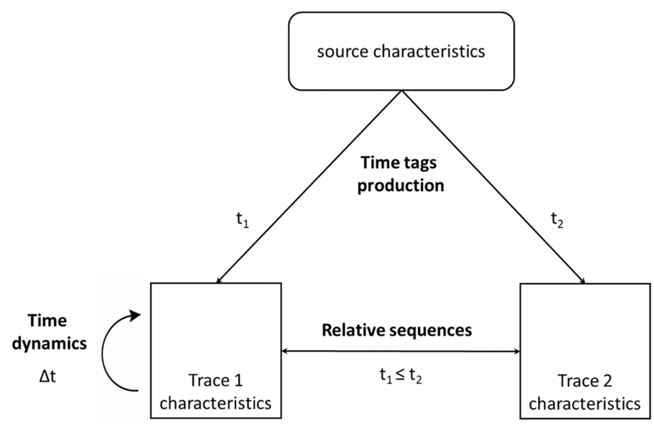

Fig. 10. Schematic representation of the three approaches that can be used to situate traces in time: *time tags* (i.e., absolute time records), *time dynamics* (i.e., duration) and *relative sequences*.

was holding his right forearm with her right hand. Several bullet holes on the walls and furniture were also used to reconstruct the sequence of event. It was inferred from those impact traces, as well as other traces (e.g., gunshot residue, relative position of the bodies and firearm) that P1 was standing at the entrance of the room when he started shooting at P3. Impact traces on the sofa and cushion on the left, as well as two bullet holes at the back on P3's jacket supported the hypothesis that she was sitting or starting to stand up when the shooting started (i.e., the first projectile passed through the back of her jacket and a cushion before ending its course within the sofa). P3 was then shot in the head at relatively close range while standing. Impacts on the wall above the window supported the hypothesis that P2 was sitting on the sofa in front of the window when P1 started shooting. P2 stood up, crossed the room and reached for P1's hand before being shot in the head. Finally, still holding P2, P1 shot himself in the head and the two fell on the floor together, with the left foot of P2 lying partially on the coat of P3. The bodies, firearm and bullet holes relative positions played a crucial role in this hypothetico-deductive reconstruction (see principle 3 of SD).

3.3.1.2. Relative dynamics. The relative values of dynamic characteristics can also be used for relative sequencing. The relative quantity of volatile gunshot residue in the muzzle of a two barrels firearm was used in a shooting case to infer that one barrel had been used twice, rather than two barrels used simultaneously [72]. This supported the hypothesis of a homicide rather than a self-defence act. The relative haemoglobin fraction of bloodstains was also implemented to infer that some stains were transferred on the scene well before others, thus indicating that the older ones were not relevant to the crime investigation [73]. Though rarely useful in practice, the appearance of wear traces on sole marks or a scar on a fingermark may also indicate a chronology between related cases in which traces from the same source are detected (see Fig. 5).

Apart from time stamps, digital traces also contain sequential information in the form of file name or entry number. This is typically the case of name incrementation used by cameras for pictures (e.g., DSC_0012, DSC_0013, …) or number incrementation used within databases to order records (in a column named 'identity column').

When a file is deleted, incremented characteristics such as, but not limited to, file names, may not be attributed again immediately (depending for example on the incrementation or allocation strategy). Similarly, deleting an entry in the Mozilla Firefox history database leaves a visible gap in the number incrementation (of the identity column) as the number that was used to describe the deleted entry will not be reattributed. Modification of the file name or a database record to remove this gap may be complicated as all the incremented files or numbers should be re-numbered in the right order, or a new file must be renamed to replace the deleted one. While this can occur for legitimate reasons, it is useful to reconstruct the sequence of creation of files and other digital activities such as messaging or web surfing to detect potential anomalies.

Several additional features related to the functioning of file systems can also be used. As mentioned before, the position of files on a storage device may offer additional time-related information if the functioning of the allocation algorithm is well-known and understood. This approach is therefore limited to the knowledge that is available or that can be acquired [62]. For example, the file system implemented on current Windows operating systems (the New Technology File System, NTFS) is not open source. Thus, the knowledge of its functioning can mainly be acquired through reverse-engineering which introduces a certain number of uncertainties. Nevertheless, if the limitations and the scope of use are known and multiple dynamic characteristics are correlated, relative sequencing can still be used to reconstruct sequences of activities or detect tampering. This holds especially true in the case of NTFS (on Windows), which uses a less predictable allocation strategy to allocate the space on the storage (best fit) [74]. In addition to the logical position of files on the storage, it is thus possible with NTFS to benefit from other dynamic characteristics such as the sequence number and the entry number that are used in the Master File Table (MFT) [75]. The MFT is an index used to record information about each file stored on the volume in the form of an entry (e.g., filename, timestamps, etc.), and sometimes the content of the file itself. Each entry in the MFT is ordered using the entry number, which is unique and incremental, and is allocated using a first fit strategy (i.e., with this strategy, the algorithm searches for the first entry available, starting from the beginning of the unreserved part of the MFT). Combined with the sequence number, the entry number can be used to infer a sequence of file creation (see Figure

9). In the MFT, the sequence number is used to describe the number of times an entry related to a file was used and is incremented each time an entry is reallocated (i.e., in the case of a deletion). Using this information, it is possible to determine that all entries with a sequence number 1 are sequenced based on their entry number. For example, a file related to an entry which has a sequence number of 1 (meaning the entry has never been reallocated) with the entry number n_1 is necessarily created before another file related to an entry with a sequence number of 1 and an entry number n_2, such as $n_1 < n_2$. In the context of a backup storage in which files are only created and never deleted, these dynamics characteristics can be used to reconstruct the sequence of file creation.

Images, text and voice messages also contain sequential information that might be useful to reconstruct chronologies. When several pictures of an event were taken, then the sequence of activities can be reconstructed without knowledge of the time interval between the pictures. Similarly, while more indirect, information can be extracted from text or voice messages. For example, if a person writes "I will walk the dog before calling you", it indicates a sequence of planned actions without any precise time indication.

4. Discussion

Three different type of time questions can be differentiated as follows:

- Did something occur at a **specific time**?
- **How long** did something occur?
- Did something occur **before, at the same time or after** something else?

The three described dating approaches can help answer these questions (see Fig. 10). Absolute time records, so called *time tags*, are often used in practice, and indicate a more or less precise point in time. Alternative approaches are usually employed when no time tag is available or when doubt exists about the reliability of the recorded time. These approaches are based on the concepts of *time dynamics* and *relative sequences*.

Time tags, particularly time stamps, are very polyvalent to answer all types of time questions (see Table 5), while time dynamics can mainly help infer about duration and relative duration. When associated with time stamps (i.e., the time of examination t_e is known), the time of the activity (e.g., time of death t_1) can be inferred using time dynamics ($t_1 = t_e - \Delta t_{1\text{-}e}$). Finally, relative sequencing is not based on time related characteristics (t), but on sequence related characteristics (s). This approach is mainly used for reconstruction purposes but can also be combined with the other dating approaches to reconstruct chronologies or detect anachronism. For example, if $s_1 < s_2$, the relative sequencing indicates that trace 1 was created before trace 2, then it can be inferred that the time of creation of trace 1 was before the time of creation of trace 2 ($t_1 < t_2$). The different approaches are often consciously or unconsciously combined in practice, to control the veracity of the temporal inferences and detect potential manipulation (e.g., backdating).

Time stamps intentionally aim at recording the time of activities and associated products such as documents, files, or manufactured objects. Thus, they are frequently used to situate traces in time in forensic, and more broadly in investigative, practice. While it could be referred as the "gold" standard of forensic dating, it also has limits such as frequent desynchronisation, loss or modification due to normal systems use and fraudulent manipulation (see principle 5 of SD [2]). Thus, while the other dating approaches (time indicators, time dynamics and relative sequences) are usually less straightforward and sometimes more complex to implement in practice, they can be particularly useful when no time stamps are available or when there is doubt about the information conveyed by them. It is particularly interesting to combine different type of traces and dating approaches for different purposes (see principle 6 of SD [2]), for example as follows:

Table 5
While time tags can help answer all type of questions, time dynamics can mainly help infer about duration and to some extent also relative chronologies. On the other hand, relative sequencing can only help to answer the last question.

Main types of time questions	Time tags (time stamps and indicators)	Time dynamics	Relative sequences (relative position and dynamics)
When?	t_1, t_2	-	-
How long?	$t_1 - t_e$	$\Delta t_{1\text{-}e}$	-
In which succession?	$t_1 \leq t_2$	$\Delta t_{1\text{-}e} \geq \Delta t_{2\text{-}e}$	$_1 \leq s_2$

4.1. to infer about unity of activity, location, and time

Time is one of the key elements in the reconstruction of events of interest, together with location and activity (principle 1 of SD [2]). Inferring that a person is the source of an activity at a specific location and time (i.e., unity of activity, location, and time) frequently relies on time independent characteristics such as DNA profiling or fingermarks, known to be very stable over a person's life span. However, when such traces cannot be detected or do not deliver useful clues, other information are used to identify people and verify their alibis. Such information was for example used, among other clues, to convict Graham Dwyer for the killing of Elaine O'hara in 2012 [77]. While the presumed perpetrator was careful not to use his personal phone to communicate with the victim, mobile phones that were associated with her and her probable killer, were found in a reservoir nearby where her lifeless body was found. Extracted information (e.g., localisation and text messages) gave information about a potential suspect. The phone location at specific times allowed to obtain pictures of the license plate of a car passing in front of CCTV cameras (i.e., supporting the identification of Dwyer as a suspect). The suspect phone locations were also the same as Dwyer's phone during some time periods. Finally, the text messages contained in the unknown phone was compared to information about Dwyer's personal life, it was found to be highly unlikely if not impossible "that another person in the world had a child born on the same day as Dwyer's child with the same name, bought a bike on the same day and got a pay cut on the same day as Dwyer".[20]. This case shows how the unity of time, location and activity supported the identification of the suspect phone's owner. Such information plays a central role to control alibis.

4.2. to corroborate temporal information

The estimation of the time since death was vastly studied using medical approaches (e.g., body cooling, post-mortem lividities, rigor mortis). Due to the limitations of such time dynamics approaches (i.e., limited time span, influence factors), other methods were developed in collaboration with other disciplines such as insect colonisation and chemical methods. However, the investigators can additionally use other dating approaches such as time stamps (e.g., last seen, last digital or physical activities, last recorded heartbeat). While all methods have limitations, a combination of several methods can be particularly efficient to increase the reliability of the estimation (see principle 5 of SD [2]). The fastest methods will be implemented in the early investigation stages, while more reliable approaches requiring more time and efforts might be useful in latter stages (e.g., in Court) (see principles 6 and 7 of SD) [2,5,78]. Another frequent example is based on images that can be important vector of temporal information. While nowadays mainly recorded in digital forms, they can still occasionally be printed on paper

[20] https://www.irishtimes.com/crime-law/courts/2023/03/24/graham-dwyer-fails-in-appeal-against-conviction-for-murder-of-elaine-ohara/ (last access June 2023)

substrate. Moreover, the downloading, copying, or sending of pictures between systems can lead to a loss of the original time stamps (see Table 1). In such cases, the content of a photography might deliver more relevant temporal information than the time stamps associated with the digital file (see for example Fig. 5). A combination of elements from different dating approaches can be used to situate a photography in time such as clocks (time stamps), objects with known fabrication date (time related data), shadows and plant seasonal growth (time dynamics). When several pictures or videos are under investigation, their content may also indicate in which order activities took place (relative sequencing). In the digital environment, investigators should look for more than time stamps (some of which can easily be tampered with or modified by normal system usage). Relative sequencing can for example be associated with time stamps to corroborate the temporal information or detect anomalies [62].

4.3. to reconstruct chronologies

Situating traces in time is particularly important to reconstruct chronologies (also called timelines) (see principles 2 and 3 of SD [2]). It is intuitively (if somewhat implicitly) done in every criminal case by investigators. Reconstruction of activities in physical crime scene environments is largely based on non-temporal information such as modus operandi or pathways inferred from witness statements, trace pattern and relative positions (see Section 3.2 on relative sequencing). However, all approaches can be combined in the reconstruction of events and digital timestamps are increasingly used in practice. Formalising dating approaches may help explicit how time related information is gathered, thus ensuring that reliability of the information is controlled, and sufficient synchronisation is achieved for the chronological reconstruction of a given case. The formalisation also allows to check that all potential venues were investigated in a particular case. When large amount of temporal data is available as is often the case in digital environments, tools were developed to automatically extract and visualise such large amounts of digital timestamps from different systems [79]. While very useful in specific and repetitive situations, such as incident response (e.g., malware detection), automatically reconstructed timelines often contain too many and insufficiently harmonised data to be relevantly used in practice [80]. The analogy with the physical world might be the swabbing of all the surfaces of a scene with several dozens of DNA profiles that later need to be evaluated. Thus, it may be essential to introduce the concept of relevance earlier in digital investigations to broaden the utility of digital traces [2,81,82]. Time, together with place and activity, can be very useful to recognise relevant traces and differentiate them from background traces (i.e., traces unlinked to the event of interest) [5,83].

4.4. to detect anomalies and backdating fraud

Combining different source of information is particularly useful to detect potential tampering as it is very difficult for a forger to correctly copy or modify all details of a legitimate activity supposed to have occurred at another time, as well as to erase all traces of his forging activities (see principle 1 of SD [2]). The Hitler's diaries represent such an example, as the forgers did not think about the type of papers used at the time they were supposed to have been written. The time stamps (i.e., dates on the documents) and other traces (i.e., handwriting) did not reveal the backdating fraud, while time related data did (i.e., optical brighteners introduced later in paper production). Casey also reported a case in which a person planned the backdating of an email from his computer to forge a digital alibi during a theft [10]. The investigators found emails that the suspect sent to himself, developing, and testing his backdating skills before the event under investigation took place. In the 2020 World Anti-Doping Agency v. Russian Anti-Doping Agency case,[21] independent experts revealed that a digital system was backdated to modify several files as if they had been created at a previous date (i.e., the backdated system date) before setting the system again at the right time. Anomalies were found during the considered time frame for the event of interest. However, experts had to look to more recent activities to detect the backdating of the system. These examples illustrate the importance to search for traces also before and after the event of interest is supposed to have occurred (i.e., planification and dissimulation traces [4]). In the same case, "WADA alleged that the evidence of fabrication, modification and deletion of Forum Messages in the LIMS database was the "smoking gun" in its non-compliance case against RUSADA" (see pages 132–139 of the report). This strong WADA assertion was based on expert's stratigraphy analysis, revealing inconsistencies between the relative sequence and the timestamps of forum related database records. Moreover, automatic processing of digital timestamps can be particularly useful in monitoring processes for example for the detection of abnormal events (e.g., ATM usage anomalies [84], timestamps manipulations [31]). Temporal data, if relevantly handled, may significantly support monitoring and intelligence processes as well [85].

As can be seen through these examples, situating traces in time can support different purposes and can serve as clues in investigations, as evidence in Court or as information supporting the production of intelligence that can feed security actions (see principle 6 of SD) [2]. Depending on the purposes, the reliability and timeliness of the information must follow different requirements, timelier for investigative and intelligence purposes and more reliable for Court purposes (see principle 7 of SD) [2,5,86].

5. Conclusion

Three main different dating approaches have been defined to situate traces in time. The first dating approach is based on **time tags** and subdivided in intentional time records in the form of time stamps (e.g., creation date of a digital file) and indirect time records in the form of time indicators (e.g., the fabrication period of a type of object). While very straightforward, time tags require scientific knowledge to be correctly searched for (without contaminating or erasing relevant traces) and interpreted regarding the risks of incorrect or misleading time information due to desynchronisation, modification or tampering. The second approach is based on **time dynamics**, i.e., measurable changes that occur as a function of time (e.g., caesium pulsation or earth rotation on its axis). Many dynamics phenomena are not only influenced by time but also by other factors rendering the implementation of this approach generally more complex. Finally, the third approach is based on the **relative sequences** of characteristics unrelated to time, such as relative positions (e.g., traces indicating a pathway or overlapping) or relative dynamics (e.g., image name incrementation on a digital camera storage device). It is routinely implemented during (crime scene) investigation to reconstruct chronologies of events.

All three approaches have potential and limits, even time stamps that are massively produced in our modern and increasingly digitalised societies. As they also give explicit time information, time stamps tend to be used to a great extent particularly in the digital environment. However, in practice a combination of approaches and traces is strongly advised to increase the reliability and utility of dating clues. As physical and digital environments are interconnected,[22] both environments should be investigated for time related information, even if the digital environment usually delivers more time related characteristics than the

[21] https://www.tas-cas.org/fileadmin/user_upload/CAS_Award_6689.pdf (last access: October 2023)

[22] There is always a human behind a machine's activities, and nowadays there nearly always is a device associated with a human activity.

physical world. It is also particularly useful to consider not only the immediate environment and time under investigation, but to look more broadly at what occurred before and after, as well as search at different locations and on different devices. While time asymmetry complicates the reconstruction of past events, it also impacts backdating operations as it is very difficult to correctly simulate the multiple traces left by an entire sequence of events. Thus, situating traces in time is a crucial, if often implicit, endeavour in forensic science. Future research should focus on increasing the reliability of the dating approaches presented in this work, by combining and systematising their usage in investigative practice, as well as for broader intelligence purposes.

The dating approaches have also been discussed under the prism of the Sydney Declaration (SD) definition and principles [2]. Indeed, traces are fundamental vector of information, including temporal information thanks to the asymmetry of time (see principles 1 and 4 of SD). Temporal information is particularly useful in crime scene investigation and reconstruction processes (principles 2 and 3 of SD). The usage of (at least some of) the proposed approaches is increasing thanks to the omnipresence of digital devices (and thus, traces) in our daily lives. However, their interpretation within case-specific context is confronted to several limitations that need to be accounted for in forensic practice (principles 5 and 7 of SD). The specific requirements depend on the questions and purposes in which the approaches are implemented, as they can support investigative, evaluative, and intelligence processes (principle 6 of SD). In conclusion, the SD principles are key principles to any forensic endeavour, including situating traces in time as demonstrated in this paper.

CRediT authorship contribution statement

Celine Weyermann: Conceptualization, Writing – original draft. **Thomas Souvignet:** Conceptualization, Writing – review & editing. **Céline Vanini:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

None.

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