Out of the Labyrinth: Leveraging Other Disciplines for Requirements Traceability

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***Abstract*—Imagine a world in which luggage never comes, Fido remains lost, forgeries cannot be distinguished from the genuine, a gallon of petrol in one gas station is not equivalent to a gallon in another, tainted peanut products cannot be recalled and disease runs rife. Without the ability to trace, one may anticipate such a world. Tracing is one of the oldest skills possessed by the human race and was vital to the survival of early hunters. Over millennia, mankind has adapted this skill to other areas, ranging from metrology to epidemiology. Software systems engineering is a relatively new discipline that employs tracing, but it appears to exhibit some unique characteristics. This paper examines tracing and its underlying concepts across a number of disciplines to highlight the specific challenges associated with tracing requirements. It draws upon these disciplines to illustrate how existing practices could be leveraged, and to clarify a priority for research and practice.**

Keywords-animal tracking; art provenance; epidemiology; food traceability; Greek mythology; luggage handling; metrology; requirements traceability; sign; trace; track; vision.

I. INTRODUCTION

Traceability is a problem so old that it is the subject of fairy tales, legends and myths. Great myths survive because they can always be retold in a contemporary way. Consider this story of software systems development in the Near East:

Minos, chairman of CRETE, was unhappy in his marriage. As compensation, he commissioned a new software system. Immediately distracted by other matters he paid little attention to defining his requirements, changing them often and seldom reading progress reports. However, he did have sufficient experience to realize that this might result in the creation of a real monster.

Minos had engaged a brilliant engineer for the project, Daedalus, but his frustrations with his client led him to build the system in a way that only he understood and without any proper documentation. Feeling trapped, he finished the job and flew off to another firm. His son, Icarus, went with him and died on the way.

The system did eventually function, but in such a complex way that it become known as the Labyrinth. Both its users and maintainers became convinced that it did in fact contain a monster, part man-made and part machine-generated, which they named the Minotaur. The Minotaur frustrated all efforts to make the system work properly and ruined many careers.

Such was the frustration of Minos that every year he demanded a fresh team of engineers, fourteen new graduates, to 'Get into that labyrinth, and kill that monster!' Every year they tried to work out what the system was really supposed to do and rectify its many faults. They always became totally lost, failed completely and were fired. Eventually, one young engineer, Theseus, met Ariadne, the chairman's daughter, who fell in love with him.

As work experience before going to university Ariadne had been an assistant to Daedalus. Occasionally, in the interest of client relations, he had explained to her exactly how he was trying to meet her father's requirements, which ones he had abandoned, what he had added and what had become contradictory. With this knowledge, Ariadne was able to show Theseus what the Labyrinth had been intended to do and how the requirements had or had not been fulfilled. With the signs she hence laid, she could then trace its functionality forwards and backwards. It subsequently became clear that the Labyrinth had multiple entrance and exit points.

With this knowledge, and motivated by the possibility of setting up his own company with Ariadne's support, Theseus was able to follow her trail, systematically examine the system without becoming lost in its labyrinthine constructs, discover both its specified and unspecified functions and, metaphorically speaking, slay the Minotaur and escape out of the Labyrinth. Ariadne and Theseus then went to Naxos to set up a software house. It collapsed almost immediately when Theseus absconded with its assets.

In the original version of this Greek myth, Ariadne made the simplest kind of track by laying a continuous piece of thread. Theseus could then trace his way both into and out of the labyrinth. Hansel and Gretel, in the eponymous Northern European fairy tale, had to recognize one stone at a time and then search for the next stone in order to trace the track which they had previously laid in the wood. In these stories, to trace means to follow a track made up of simple signs, one continuous sign extending right into and out of the labyrinth and one linear pattern of signs through the wood. Traceability, in both cases, depends upon the availability of a track and the ability to identify who or what made it.

In software systems engineering (SSE), the basic idea of tracing a requirement forwards and backwards appears straightforward, but achieving this traceability remains demanding in practice. The lack of comprehensive methods suggests that traceability is not such a simple concept and that requirements traceability presents special difficulties. We suggest that tracing requirements is a difficult problem and that part of the solution is to be clear about the nature of this difficulty. Fortunately, there are many established disciplines where traceability, though not always called exactly that, is so important that difficulties have been overcome and we look to them for some enlightenment.

In examining other tracing disciplines, this paper presents a conception of requirements traceability that might appear in contradiction to prevailing research trends. We argue that requirements traceability demands special preparations. Rather than being passively sought, it must be actively generated. This paper aims to engender a vision of a future

where proactive requirements sign making is a core element of SSE and of development environments.

In Section II, we describe the role of tracing in six disciplines (animal tracking, art provenance, epidemiology, food traceability, luggage handling and metrology), an illustrative but not exhaustive list of the fields in which traceability is always a fundamental issue. In Sections III, IV and V, we undertake a systematic and comparative analysis of how three interrelated concepts underlying the ability to trace are implemented in these disciplines. In Section III, we define the first of these concepts, the *sign*, and consider a set of related factors in the analysis. A table relates each of the factors to each of the six disciplines and shows how they often differ significantly in implementation. Sections IV and V examine the concepts of *track* and *trace* in the same manner. Section VI then considers signs, tracks and traces in SSE and draws upon the prior analyses to articulate the special difficulties associated with tracing requirements. Section VII highlights how existing practices within established disciplines could be leveraged to address some of these difficulties, and lists priorities for research and practice. Section VIII concludes the paper.

II. TRACING IN OTHER DISCIPLINES

The six disciplines examined in this paper were chosen because of the importance that they themselves place on solving tracing problems in widely different contexts and environments, and because each is sufficiently mature to have its own well documented story. The role of tracing in these disciplines is described below.

The skills and discipline required to track an animal in the wild are probably even older than the myths of antiquity. The motivation of the hunter was simply the finding of food. Finding, identifying and following the signs left on the ground or in the environment remain fundamental to this activity [5]. These signs form the track, left automatically by physical impacts of some kind. The objective of the tracker is to trace the path taken by his or her quarry by the means of finding and following its track. Figure 1 illustrates the necessary distinction between the track of signs and the trace created in following that track. The trace, in effect, recreates the track and hence shows the movement or progress of its producer, the real subject of interest.

Being the oldest tracing discipline examined, animal tracking suggests how three fundamental concepts (sign, track and trace) might properly be reformulated for the newest, SSE. The factors that the other disciplines emphasize in their own practices then provide the framework through which these concepts are analyzed in Sections III, IV and V.

In the worlds of academic art history and the art trade, tracing the 'provenance' of a work (meaning 'origin' or 'source') is all-important. Establishment of the authenticity, and hence the value, of a work requires evidence, preferably in the form of original documents, tracing an unbroken succession of owners from the original creator to the current owner. The issue of available documentation is critical because, unlike other objects of trade such as aircraft, works of art do not automatically carry their own paperwork with them. Creating the provenance for a work, therefore, requires the identification of all transfers, the points at which possession switched from one owner to the next [15].

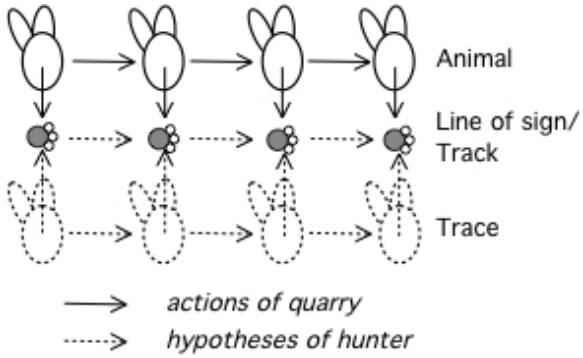

Figure 1. Sign, track and trace differentiated.

Tracing an outbreak of a disease, forwards from all infected persons to all possible contacts, and tracing backwards to its source, forms the essence of epidemiology. “Epidemiology is the study of how often diseases occur in different groups of people and why.” [7]. The epidemiological investigation process begins by first confirming that a particular disease outbreak has occurred. It is then critical to trace the source, cause and mode of transmission of an infectious disease in order to understand its potential spread and to plan necessary control procedures in a population [1]. With this information, the disease can then be followed over time and data on the appearance of cases can be plotted as an epidemic curve for analysis [14].

The ability to trace the path taken by all the components finally incorporated in any food product is fundamental to food safety. The information available from tracing food processing facilitates any necessary recall. The food industry has promoted the principle of 'one up / one down' origin and destination information to simplify the creating of data and the tracing of what may be large and complex patterns of supply and distribution [9]. This principle is the basis of an agreement to maintain records about the immediate supplier and the immediate subsequent recipient of a food product at all points along the food chain [4]. Consumer concerns about the origin and nature of food has also motivated the simplest form of tracing that can be achieved via labeling.

Tracing luggage is a problem familiar to all airlines and their customers. If the owner of an item of luggage does not board an airplane for which he or she is checked in, then the luggage has to be retrieved and removed. If an owner does not receive his or her luggage at the correct destination, then the luggage needs to be found and forwarded. Lost luggage is a problem of real consequence to the airline industry, costing $3.3 billion dollars in 2008 [2]. Multiple problems and possible solutions are identified in the worldwide Baggage Improvement Program of the International Air Transport Association [10]. This envisages the real-time visibility of luggage and provides high-level guiding policies within which individual airports and airlines can operate consistently, but independently. A problem with as many causes as lost luggage demands a holistic solution.

Traceability is a core concept in metrology because this discipline is concerned with the maintenance of accurate, repeatable and interchangeable measures via reference backwards to internationally or nationally accepted standards. Metrological (measurement) traceability is defined as the "property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty." [11]. Creating a claim of metrological traceability, therefore, involves documenting the relationship of a measurement result to a reference representing a 'higher authority' [12]. A measurement result on a given instrument is thus expressed as a quantity value, coupled with a quantitative statement of its measurement uncertainty, derived by tracing backwards to the original standard.

In each of these disciplines, the need to trace is triggered by movement, be this of animals, ownership, disease, food, luggage or instrument precision. If nothing changed in space or time, everything would remain at rest and traceability would have little meaning. Requirements are but one in a long line of entities that are 'in motion' and we seek to learn from those disciplines that handle such motion successfully.

III. SIGN

A simple definition of a sign as "any physical indication left on or in the environment by the passage of an animal" derives from the discipline of animal tracking [5]. It requires that the sign maker should, autonomously and automatically, provide a unique identifying mark on its surroundings. However, as shown in the previous section, there are entities that their owners or others wish to be traceable but which cannot themselves produce identifiable signs automatically on their environment, if they make any signs at all. The sign-making animal makes its own sign, but an item of luggage requires a separate sign maker to act on its behalf and to create a sign associated with it. A sign becomes, more generally, *'an identifying mark made by, or associated with for a particular purpose, an animate or inanimate object'*.

The sign maker either identifies itself directly, as does the animal or the pathogen causing an epidemic, or identifies something else by some form of association, as does the factory worker attaching a label directly to a consignment of food. Indirect attachment also occurs when some form of documentation, for example a sales list from an auction house, identifies the transfer of ownership of a work of art.

A number of factors are closely related to the concept of sign. These have different significance in each of the disciplines and are set out in Table I[1]. The questions addressed are: What is the animate or inanimate entity of interest (signed entity)? What is it that marks the 'movement' of the signed entity (sign)? Who or what makes the sign (sign maker)? Is the sign associated with or directly made by the sign maker (mode of sign)? What carries or bears the sign (medium of sign)? What does an instance of a sign stand for (sign represents)? How long will a sign survive (permanence of sign)?

[1] Tables I, II and III can be found at the end of this paper.

In comparing how the disciplines account for signs and their related factors in Table I, a number of observations can be made. First, the sign maker and the signed entity are one and the same when the signed entity is capable of leaving its own signs in the environment through which it moves (e.g., animal tracking and epidemiology). In animal tracking, the sign (i.e., the animal print) is unique to an animal species and often quite straightforward to identify, if clearly imprinted. However, isolating a particular individual of the species can be more problematic and is dependent upon heuristics (e.g., consistent size and spacing in the print). In epidemiology, identifying the type of pathogen causing a disease is difficult where the signs (i.e., the symptoms of disease) are common to many diseases. In both disciplines, only the isolation of an instance can lead to the precise identification of the signed entity, thus confirming its sign.

Second, where the signed entity is inanimate and incapable of leaving its own sign, some external agency needs to provide it with one. This sign can then be directly attached to the signed entity (as in food traceability and luggage handling) or is not attached (as in art provenance and metrology). In the pair of former cases, the signs are designed for tracing and the focus is on assuring the attachment. In the two latter cases, the attachment is indirect, so standards for data recording, storage and retrieval are vital to gain the association, something that is planned for and evident in metrology but mostly accidental in art provenance.

Third, where the sign maker is an individual, there is usually some consistency in the sign making, easing the identification of related signs over time. Where many parties assume the role of sign maker, this adds potential sources of inconsistency in the sign making, leading to possible identification problems. Mature disciplines have industry standards and codes where sign making is a team effort.

Fourth, the medium that carries the sign dictates its permanence. The most impermanent sign is a direct sign in a changing environment, as with animal tracking and epidemiology. Without timely action, in following or recording, the signs disappear. Where a sign is associated and attached, the permanence also depends upon the security of the attachment. Novel approaches have been designed to attach associated signs more permanently to signed entities, such as by placing RFID or GPS chips inside food and luggage. Where a sign is associated and not attached, the permanence further depends upon the ability to maintain a link to retrieve the sign. Direct attachment is not really possible short of damaging a work of art and, in metrology, differentiating any sign from its predominantly numerically signed entity would become a new problem. Separation of signs and their signed entities presents a challenge.

IV. TRACK

For the tracker following an animal, a track is simply "a line of sign" [5], which, by virtue of the shape of each sign, also indicates a single direction for the quarry. In the case of multiple signs, or lines, the problem is to isolate the signs and the line belonging to the individual making them. The pattern of the track is certainly not linear where sign makers multiply, as in the case of the pathogen infecting multiple

contacts and creating a tree-like pattern for its track. In forwards tracing of a pathogen these multiple contacts themselves each become the root of a new tree. In backwards tracing, as in the case of the Broad Street pump which was the origin of the London cholera outbreak famously identified by Snow in 1854 [13], the pattern appears as a star. More generally, therefore, the track is defined as *'a pattern of signs created as these signs are generated'*.

The characteristic pattern of the track identifies the position of each sign relative to the next and hence the process that will be used to find it. In the case of a pathogen, this will be an exhaustive search for all possible contacts, whereas for an animal it will be for the single next sign at an anticipated position, the expected pace length of the individual being followed. Any position where an expected sign is not found acquires the status of a potential gap in the track, which also requires a set process to fill [5].

As with sign, a number of factors are related to the concept of track and have different significance in the disciplines. Table II sets out the factors and key observations are summarized below. The questions addressed are: What activity causes a track to be made (cause of track generation)? Who or what creates the track (track maker)? What does an instance of a track stand for (track represents)? What shape does the track have (pattern of track)? How does the track begin and end (origin and destination of track)? How long will the track remain (permanence of track)?

First, Table II shows that the track maker may not be the same as the sign maker over the entire track. Where they are one and the same (e.g., same animal), it is generally easier to see the consistency between the signs and so establish the track. While the code associated with an item of luggage remains the same from one track position to the next over a journey, being registered at different positions, the code associated with food may be superseded along the track as the food is processed and new codes are overlaid. Where the signs vary more dramatically, as in art provenance, this can lead to potential complications in establishing the track; not only is the sign maker at each position in the track not known in this case, the sign itself cannot be predetermined.

Second, the track is established due to some continuity of sign. However, no physical continuity exists in metrology, so the link between successive signs needs to be made explicitly to establish the track, choosing and documenting the standards that the measurement result is anchored in. Uncertainty in the track is, therefore, recognized explicitly in metrology. The link is created likewise in art provenance, but based upon semantic continuities in the ownership concept.

Third, the concept of track origin and track destination is important to each of the disciplines, though identifying one may matter more in any particular discipline. In animal tracking, the origin can be anywhere along the 'extended' track. It is effectively where a sign is first identified and from which it is subsequently pursued, since it is a path to the destination that matters. In luggage handling, the quality of the sign made at the origin is crucial to the subsequent track, without which the intended track would not be defined. While the visibility of luggage at all positions along its track may be useful for retrieval, getting the luggage to its intended destination is the main goal. The origin of the track is critical for art provenance, but any claim depends upon the destination being current ownership. Likewise in metrology, a full track that is unbroken between established endpoints is fundamental. The availability of the overall pattern of track matters to epidemiology and food traceability, but while the track of a food product may have well defined endpoints, the destination of an epidemiological track may remain open.

Fourth, the track in each discipline shows movement, in physical space, custody, food constitution or precision. The pattern of track indicates how many signs are being looked for at a particular position and, in some cases, where to look. A single linear path of signs is generally the easiest track to establish and regain. The greater the spacing between sign positions, however, the more difficult, as in art provenance where ownership may only change by generation. Where the track exhibits multiple paths, as in epidemiology, the overall pattern can help in the identification of a particular disease and in the prediction of its future track. Track pattern has real significance and value for analysis capability in this case.

V. TRACE

By exploiting the earlier definitions, 'to trace' now means, *'to identify a track following its pattern sign by sign'*. A trace is the product and record of that activity. It represents and stands for the activities that caused the track to be made, for example, the animal in motion or a disease spreading through a community. Traceability is *'a quality of an entity allowing it to have a track, howsoever made, plus the availability of a means to follow that track'*.

In the case of an animal, traceability only requires a medium, such as soft mud, which will allow signs to be made and remain long enough for a tracker to find and interpret them. In the case of airline luggage, however, traceability necessitates a standard code of origins, destinations and flights, a means of attaching them to every item of luggage, a person or machine to make the attachments, a network of persons or machines located at every position on the possible track, the activation of this network so that codes and machines will interact to 'fill' a particular position and, finally, persons or machines to identify the fact that the particular position has been filled by an identifiable item and hence is able to generate a trace which shows where the item of luggage is or last was.

The example of luggage handling also illustrates the related concept of a trail, as *'a track laid with the intention of being traced'*. Every item of luggage is given a predefined track (e.g., LHR to JFK to LAX) along whose positions machines or persons will expect to be able to trace it (i.e., a trail). Ariadne laid her thread as a trail for Theseus; Hansel and Gretel laid their stones as a trail for themselves.

As with sign and track, a number of factors are related to the concept of trace and have different significance in the disciplines. Table III sets out the factors and observations are summarized below. The questions addressed are: What is the intention behind the trace (trace objective)? Does the trace go one way or another (direction of trace)? Who makes it (trace maker)? Who uses it (trace user)? Who benefits from its creation and use (trace beneficiary)? By what actions does

the trace come about (trace process)? What assists trace making (aids to tracing)? What happens if there is no sign where one is expected (impact of gaps in tracing)? How long will the trace remain (permanence of trace)?

First, Table III shows that the trace maker may not be the same as the sign maker or track maker. One exception may be where an animal consciously uses its own track to follow itself (i.e., to backtrack). Making a trace involves identifying a track by following its pattern sign by sign; a trace exists when an agency interacts with the signs in a track for a purpose and, in all of the disciplines, the objective for tracing is clear. Equally, the trace user is not always the same as the trace maker. In particular disciplines, such as metrology, the responsibility for claiming and then validating the traceability lies with different parties, which serves to strengthen the trust in what the traceability enables (i.e., confidence in a measurement result). Furthermore, the beneficiary of the trace may be neither the trace maker nor the trace user. Where the trace beneficiaries are global (e.g., society) there is more emphasis on standard processes and in recording the track for subsequent trace use, something needed for making and examining assurances of safety.

Second, where there is a gap in the track, the impact on the tracing varies across disciplines. Gaps always negate the trace in both metrology and art provenance, and usually in food traceability. Other disciplines have evolved strategies to accommodate gaps, generally by going back to where there is the certainty of a sign. The greater the distance between the track making and the trace making, the more potential there is to encounter gaps, as in art provenance. In those disciplines where multiple types of sign can be made, this can be used to advantage in dealing with gaps. For example, where an animal sign is expected but missing, alternative signs in the flora may assist. Where luggage and its associated sign has been damaged, either may leave evidence of passing, and this can help in regaining the track.

Third, while the processes and aids for tracing are discipline-specific, they all tend to include systematic processes, standard signs, agreed roles and responsibilities, and visual aids. The most sophisticated aids appear to have emerged in those disciplines where traceability is essential to public safety, as in epidemiology, food traceability and metrology, and more recently in luggage handling.

Fourth, once a sign has been created and participates in a track, the sign itself may change, invalidating the track and its trace. This is most obviously the case in metrology where the precision of a measurement instrument used for calibration begins to degrade, demanding re-calibration. Where the potential to trace may persist, the value and relevance of doing so may not, but in none of the disciplines is the quality of traceability discussed or measured.

VI. Signs, Tracks and Traces in SSE

To understand the characteristics and challenges of the traceability demanded in SSE, we examine the signs, tracks and traces of requirements tracing in a similar way to the previous sections. We highlight those issues that overlap with those of other disciplines and those that are somewhat special. Rather than adding a final SSE column to Tables I, II and III, we italicize the relevant points below.

A. Sign in SSE

Signed entity. *The signed entity in SSE is an individual requirement, in some way expressed, generated or inferred.* Other disciplines assume that the basic entity of concern always has some kind of significant sign associated with it, even if this reference point must be created by an external agency. Recognition of the potential for fragmentation via decomposition, amalgamation, aggregation or partial implementation makes it difficult to envisage a requirement as a single bounded entity that might be associated with some single sign. SSE deals simply with 'entities' rather than with 'signed entities'. Further, there is no detailed or standard taxonomy for requirements that might help identify different entities relevant in the field and hence their different signs.

Sign. *The sign must comprise some evidence of a relationship between an individual requirement as a concept and an engineering artifact that expresses that concept in some recording medium.* This definition is general because no requirement is already associated with any standard form of sign and none can directly create its own signs. Coming, as requirements do, in many forms and none being uniquely identifiable, the exact nature of any sign that could be left to represent the presence and affect of any one requirement is an open question. The nature of the sign may also change according to the stage of development at which it appears, most obviously very different in specification and in coding. By contrast, signs have been carefully codified in other disciplines, via field manuals for trackers or international standards for luggage codes. Even in art provenance, production heuristics indicate what types of documents might contain which forms of evidence for particular types of work in a precise period. Standardization of any kind is predicated upon the notion of a carefully defined signed entity with which a sign should or might be associated.

Sign maker. *Any sign would be created directly by engineers and other stakeholders in SSE, or created indirectly (and potentially automatically) via their activities when using development environments.* Other disciplines recognize the need to designate a specific sign maker to create and often to attach signs, playing a clear role within a fixed process. Metrologists calibrate instruments one with another and thus create a standard metric for each result. Animals make direct signs and are both sign maker and signed entity in a process that is autonomous and automatic.

Mode of sign. *An individual requirement can leave a direct sign in the form of its semantic content being replicated or semantically equivalent across engineering artifacts.* However, such a direct sign is not necessarily the unique sign of a requirement, as a paw print is of a cat. *Associated signs can exist in the form of meta-data, either attached to the signed entity by being present in the same artifact, or unattached and linked in some way (e.g., unique identifier).* In other disciplines, a specific mode of sign is the standard and processes are fixed in relation to that mode.

Medium for sign. *Multiple media may carry evidence of the signed entity as requirements may be expressed in*

natural language text, diagrams, videos, code, etc. An issue in SSE is differentiating any sign from its medium and from the wider environment in which it is carried, as it may be near impossible to find evidence of a requirement in a video. Other disciplines have eliminated this problem with unambiguous boundaries between sign and vector.

Sign represents. In general, *a sign would represent the status of an individual requirement's implementation at a stage in the development process*. The uncertainty associated with the multiplicity of requirement types and the possible signs they make contrasts sharply with the certainty given to representation via standardization in other disciplines.

Permanence of sign. *A new sign may replace an existing sign at any time in SSE as development proceeds, but any original sign would remain where there is versioning.* In metrology, all measures are time-stamped to ensure calibrations are up-to-date, while the pathogens of epidemiology eventually die. In SSE, however, the signs associated with requirements proliferate and rarely vanish.

B. Track in SSE

Cause of track generation. *Tracks may be laid for many reasons in SSE, such as the: (1) movement in the abstraction level of a requirement; (2) change in the detail of a requirement; (3) derived requirements; and (4) association of related requirements.* In all other disciplines, the signs and the track that they compose are laid prior to any tracing activity. In the absence of specific sign generation in SSE, it is difficult to talk of track generation per se because tracing may itself cause the first recognition of some impact of a particular requirement or of some succession of impacts in different positions in the development process, which together might be called a track. Previously unconnected signs become a track as they are revealed by the trace.

Track maker. *Whoever or whatever drives sign production via development activities is a potential track maker in SSE; it can be multiple human or automated agencies.* SSE lacks the level of sophistication of other disciplines where there are specific responsibilities.

Track represents. *A track may represent many things in SSE, such as the: (1) chronological trajectory of the development process; (2) its logical trajectory; (3) cause and effect relationships between artifacts; and (4) versioning of artifacts.* Because of the clarity with which the signed entity is defined in other disciplines, it is possible to be clear that the track represents, for example, the sequence of changes of ownership of a work of art from its creator to present owner. Tracks need to be re-purposed in SSE.

Pattern of track. *The pattern of track is variable in SSE.* What is common is that the requirement specification, the signed entity in its purest form, acts as a connection between two patterns, one of requirements production and one of requirements deployment. While there are other patterns, there is a dominant linear temporal pattern organizing signs by time and version. The pattern of track in other disciplines is well understood and possibilities for shape are accepted and integrated into their objectives, as in epidemiology.

Origin of track. *The origin of the track will be the point(s) at which a requirement is generated, expressed or inferred.* However, the origin of a requirement may not actually be captured or may be ill defined. Generation in a specific document or expression in the record of a meeting may both originate a requirement contemporaneously, but inference from an early design sketch may happen much later in the process. In SSE, it is possible to start laying a logical track from any point; there is no obligatory time sequencing. This is not the case in any other discipline where track laying always reflects chronology in some way, starting from fixed points of origin, such as a specific farm.

Destination of track. *The destination of the track will be the point(s) at which a requirement is fully satisfied at a relevant stage in the development process, or eliminated.* There can be no basis for a full requirements trace without a statement, explicit or inferred, of what will satisfy a specific requirement at particular stages. Success criteria in other disciplines (i.e., track endpoints) are all relatively clear.

Permanence of track. *The potential mutability of a sign as a requirement passes from stage to stage in a development process makes track identification, and hence track permanence, uncertain.* Potential mutability of the signed entity itself, and of potential interpretations of it, exacerbates the problem. With versioning, however, all tracks are permanent in theory, although their relevance may not be. Erosion of the environment on which signs are made is not a problem as it is, for example, with animal tracks or with the destruction of documentation related to works of art, unless the signs become embedded within legacy systems.

C. Trace in SSE

Trace objective. *There are multiple objectives for tracing in SSE, such as to: (1) validate and verify requirements; (2) assess the satisfaction of requirements; (3) analyze the impact of changing requirements; and (4) assist in making changes to requirements.* In sharp contrast to other disciplines, SSE attempts to satisfy multiple objectives for tracing without prioritizing them and without distinguishing between the precise types of trace necessitated in each case.

Direction of trace. *The trace direction is backwards and forwards in SSE to meet the above objectives (e.g., forwards for verification and backwards for validation).* The directionality is clear in all the disciplines, bi-directionality also being essential to epidemiology and food traceability.

Trace maker. *The trace makers are engineers in SSE, using manual or automated techniques.* In many other disciplines, the trace maker is fortunate in that a track has been laid for tracing (i.e., a trail). In the case of metrology, food traceability and luggage handling, tracing is a team effort with specific roles assigned to members. In SSE, the trail concept does not exist and the maker of the trace has no generally accepted position within a development team.

Trace user. *The trace users are engineers, perhaps overlapping with the trace makers, and other stakeholders too in SSE.* Such an overlap also exists in animal tracking, art provenance, epidemiology and luggage handling.

Trace beneficiary. *The trace beneficiaries are also engineers and other stakeholders in SSE, but this group may be wider in scope.* A successful trace in other disciplines is of direct and immediate benefit to specific stakeholders. A

passenger gets a bag; a manufacturer can recall food; a disease carrier can be identified in time for treatment; a work of art immediately increases in potential value to its owner; a hunter gets the quarry. In each case, the processes are designed to ensure this immediate benefit. Tracing a requirement does not always achieve such an immediate and clear benefit to a generic engineering role, having no direct and unavoidable impact on the development process.

Trace process. *Engineers may establish links between engineering artifacts explicitly at the time of development in order to facilitate subsequent tracing. Alternatively, the links may either be established implicitly when working in a development environment or recovered automatically later.* In all cases, connections are sought between the engineering artifacts. It is assumed that people look for semantic similarities to make these connections, something that is exploited in automated techniques. The generic link concept used in SSE places emphasis on the continuity element in a track and in the process being executed or followed. The link is analogous to the movement of the animal between making a sign at one position followed by making another sign at the next position. In all other disciplines, the emphasis is on the sign, the finding of a sign and then the finding of the next sign in a hypothesized pattern; establishment of a link between the two signs is the end product of the trace rather than its starting point. It is as if the process is reversed in SSE, the link being found first and then its specific start and end points. An identified track has become a coincidental byproduct of a trace rather than the basis for trace creation.

Aids to tracing. *Some development environments create tracks for tracing automatically as a by-product of tracks formed by development processes. A number of automated techniques for trace recovery and maintenance are finding their way into such environments.* In other disciplines, the emphasis placed on the sign and the patterns discernible in any set of signs are essential aids to tracing. Detailed rules and procedures in metrology provide aids on this basis.

Impact of gaps on tracing. *A gap exists when a sign is expected but not present, or when the position is filled with something unexpected. Some gaps in the track can be bridged when tracing requirements, recovering the track using linguistic and information retrieval algorithms.* The primary cause of uncertainty in all other disciplines is the possibility of a gap in the expected track. In SSE, the uncertainty is normally perceived as a semantic characteristic of the link, and is rarely expressed. Both epidemiology and metrology factor the concept of uncertainty and a measure of its probability into the traceability explicitly.

Permanence of trace. *Any engineering artifact can change at any time in SSE, potentially impacting others to which there is a link. The validity of a current trace may then be negated.* Each change produces some new sign, hence a new track, and renders necessary a new trace. Versioning ensures that old traces remain accessible, through recording or remaking. In other disciplines, as in art provenance, a new or revised trace automatically supersedes its predecessor, which can then be safely abandoned. In metrology, a trace decays without the periodic recalibration of its measurement instruments. Only in epidemiology and SSE, and potentially in food traceability, does the quantity of what is being traced keep growing. One infected host is not, however, versioned over time, only in the exceptional case of significant mutation. In contrast, versioning is standard in SSE, meaning that tracing becomes two-dimensional. Adding this dimension presents complexity not seen elsewhere.

VII. Leveraging Other Disciplines

In examining the tracing concepts systematically, it can be seen that SSE presents unique characteristics and challenges when tracing requirements. Most significantly, its *signed entity* is vague and its *sign* even more so. Better sign making and association is fundamental to any advances that can follow. However, it can also be seen that these other disciplines provide examples and practices that we can leverage. Requirements tracing certainly demands as sophisticated a system as that for ensuring the timely delivery of a passenger's luggage, so we use luggage handling as the exemplar to demonstrate this potential. We indicate priority areas for research tasks that are either theoretically (TR) or practically orientated (PR), or which demand associated improvements to process (PI).

A. Sign: Research priorities

Delineate a rich taxonomy of requirements (TR) The standard classifications used for different types of air cargo, its *signed entities*, provide a model for what might be a more detailed taxonomy of requirements that improves on the use of typical functional and non-functional distinctions.

Define standard signs for requirement types (TR) The well-known and standard codes used on airline luggage, the *signs*, suggest the need to pay attention to how particular types of requirement come to be expressed and implemented in their own ways, how their effects become manifest and hence what standard signs may be associated with them.

B. Sign: Dependent tasks

Characterize modes for requirements signs (PR) Standard labels fixed to luggage are supplemented by documents, such as cargo manifests listing the contents of planes. These represent attached and unattached signs associated with signed entities, the *mode of the sign* chosen as the most fit for purpose. There is a need to identify the most suitable mode of sign to associate with different requirement types and to form tracing processes accordingly.

Differentiate requirements signs from their media (PR) Signs are easily differentiated from the *medium for sign* when carried as codes on luggage. There is a need to recognize the signs of requirements as carried by diverse media and to distinguish them within their environment.

Representational clarity of signs (TR, PR) Standard codes used to identify airports (e.g., JFK) are part of a larger taxonomy of signs and of what each represents. Any useful taxonomy of requirements should incorporate both standard signs and what signed entity each standard *sign represents*.

Understand the longevity of requirement signs (PR) Once registered by scanning equipment at an expected destination, or by eye, the coded luggage label becomes irrelevant and any record can be abandoned; the *permanence*

of sign becomes irrelevant. However, during its journey and at each position on its track, the sign created for the luggage remains necessary until a new position is reached. The role of the most recent and previous records in any track of requirements is less clear, as is its degree of permanence.

Role of requirements sign maker (PI) There are many roles within luggage handling systems each with detailed processes to follow, including those for check-in clerk, the initial *sign maker*. Identifying and fixing the role of sign maker for requirements is a prerequisite for sign making.

C. Track: Research priorities

Origin recording in SSE (PR, PI) *Origin* recording is a fundamental issue in luggage handling, also associated with other issues such as limiting luggage only to that belonging to passengers actually flying. There is a basic need to define the origin of all requirements in order to provide a starting point for all forwards tracing and an endpoint for backwards tracing. Trusted anchors, so central to metrology, would provide a firmer basis in which to ground requirement tracks.

Attend to requirement satisfaction (TR) The *destination* is easy to define with luggage, although partial satisfaction (e.g., lateness of delivery) can blur the issue. Establishing what exactly will satisfy a requirement (i.e., to define its destination endpoint) should be a basic objective.

Explore and exploit patterns of track (TR) Luggage systems accept the option of many possible tracks, although all of the same *pattern of track* (i.e., linear and single direction, even if a position is passed twice). There is a need to uncover what patterns there may be in requirements processes and to understand what is typical and atypical. Track laying activities in different development process, and how these might affect tracing, are important issues.

D. Track: Dependent tasks

Identify what impacts track permanence (PR) Luggage handling systems maintain records at every potential track position until the signed entity reaches the final designated position. There is a need to understand and account for requirement and sign mutability as factors affecting the *permanence of the track* created by these signs.

Detect purposeful track creation (PR, PI) Luggage systems distinguish between the expected track of a signed entity and the network of possible positions where signs may be recognized. This creates the possibility of generating an alternative track. The *cause of track generation* is the passing of the luggage and its label. There is a need to distinguish the activities of sign and track creation that are intended in SSE from those caused by random or detrimental factors.

Role of track maker (PI) Once an initial label has been printed and attached, the track making in luggage handling is potentially completely automated via the machines at each track position reading the labels. This specific *track-making role* is generally absent in SSE unless a fully automated development environment is being used.

Clarify the trace to track relationship (TR) In luggage handling, it is clear what the *track represents*; it is the sequence of positions of a signed entity in space and time. There is a need to be more specific about the purpose of any trace of requirements, the form of the track which will need to be available and hence the signs which will compose it.

E. Trace: Research priorities

Understand and specify trace objectives in SSE (PR, PI) Luggage handling has a primary *trace objective*, to deliver bags to owners at their final destinations, but also contributes to general objectives such as flight security. To differentiate between tracing objectives in SSE, to prioritize them and establish the procedures best suited to each, would bring practices closer to those in other disciplines.

Define the goals of SSE trace beneficiaries (PR, PI) There is no doubt that the passenger getting his or her bag is the main *trace beneficiary* of a luggage handling system. Specific beneficiaries for tracing, their major goals and their role in the process, need to be more finely pinpointed in SSE.

Deal with inevitable tracing gaps (TR, PR) The *impact of gaps on tracing* is fully recognized in luggage handling. Automated sign registration ensures that a coded label inappropriate to its location is flagged. Factoring uncertainty into requirements tracing processes may be possible via the concept of sign and sign appropriate to position.

Discriminate between trace maker and user (PI) The *trace maker and user* may be overlapping in SSE. In luggage handling, roles specific to each position in any potential track are set, most crucially at its origin and destination, with responsibilities and processes defined. Definition of the trace maker role and its distinction from user role is fundamental.

F. Trace: Dependent tasks

Build directionality into sign making (PR, PI) Food processing is the best example for *direction of trace* because of the complexity of the entity combinations involved, and the restricted 'one up / one down' relation and record at any position on a track. Such potential for bi-directionality needs to be built into the sign making process in SSE.

Role of standard signs (PR, PI) The fundamental role of standardized codes in luggage handling facilitates a standard *trace process*, but one that can accommodate variation. The sign itself, and its marking on some signed entity, have roles in facilitating all effective trace processes. SSE lacks these standard codes and practices. It thus lacks the capacity to support variations in its processes easily.

Informed use of automation (PR) The environment of people and machines spread over locations to facilitate luggage handling suggests the usefulness of reassessing SSE development environments, automated or not, in terms of their suitability for sign creation and as *aids to tracing*.

VIII. CONCLUSIONS

Theseus encountered in Ariadne a requirements tracing heroine. Sadly, there is no record of how she laid her track of signs through the Labyrinth system, nor of their nature. What is certain is that Theseus traced his way in and then out using these signs, and that his story illustrates the long-understood principle that there is ***no ability to trace without a track and there is no ability to lay a track without making signs***.

Requirements traceability must be the subject of special preparations such as those given to traceability elsewhere.

Active generation of traceability demands attention not only to the possible changes to practice highlighted in the previous section, but also to those offered by other tracing disciplines. We present one extra observation here. Only a single signed entity is ever traced at any one time, except in epidemiology, which traces instances of a pathogen type. In SSE, we attempt to trace potentially thousands of signed entities, representing different types and instances of requirements, before we have demonstrated the capacity to trace just one efficiently and effectively. As a newer tracing discipline this should be our immediate goal. Its achievement would mark a step towards realizing a vision of proactive requirements sign making as a core element of SSE and development environments, irrespective of whether our signs are ultimately created and linked manually or automatically.

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TABLE I. DECONSTRUCTING THE CONCEPT OF 'SIGN' IN THE DISCIPLINES (SEE SECTION VI TO COMPARE 'SIGN' IN SSE)

Factor	Animal Tracking	Art Provenance	Epidemiology	Food Traceability	Luggage Handling	Metrology
Signed entity	An individual animal.	An individual work of art.	Multiple instances of an individual pathogen.	An individual food product.	An individual item of luggage.	An individual measurement result.
Sign	An animal print or some disturbance in the environment (e.g., droppings, hair, etc.)	A record of the transfer of ownership and / or location of a work of art.	Some physical symptom of disease in a person or animal.	An industry standard code, appropriate to different stages in the food chain.	An industry standard code.	A metric that quantifies a measurement result, its uncertainty and a link to a reference standard.
Sign maker	The individual animal.	Multiple persons (e.g., buyers and sellers of art, art collectors, auctioneers, etc.)	An instance of the individual pathogen.	Multiple persons or systems, recording the processing and movement of the food product.	Multiple persons or systems, recording the movement of the item of luggage.	Multiple persons performing and recording measurement results, and calibrating instruments.
Mode of sign	Direct. The sign is made unconsciously by the signed entity.	Associated, but not attached (i.e., held separate from the signed entity).	Direct. The sign is made unconsciously by the signed entity.	Associated and attached directly to the signed entity.	Associated and attached directly to the signed entity.	Associated, but not attached (i.e., held separate from the signed entity).
Medium for sign	The ground and wider environment.	A document of no standard type or format.	A person or animal.	The food product is marked directly with the sign, or a 'label' carrying the sign is attached to the food product or its packaging.	The item of luggage is marked directly with the sign, or a 'label' carrying the sign is attached to the luggage or its packaging.	A document of standard type and format.
Sign represents	The position of the animal in space and time, and its probable direction of movement.	The ownership or location of the work of art in space and time. It may indicate the prior and future intended owners or locations.	The infection of that person or animal at a moment in time and in space. The origin and destination of the pathogen is not inherent in the sign.	The processing that occurred to the food product at a place and time in the food chain, with defined immediate supplier and subsequent recipient.	The intended position of the item of luggage in space and time, and the actual position once the sign is registered. Inherent direction of movement.	The accuracy of a measurement result at a particular point in a calibration chain. Directionality is inherent in the link to the reference.
Permanence of sign	Impermanent and degrades with environmental disturbance. A potential for fossilization.	As permanent as the medium of the documentation carrying the sign.	Impermanent and potentially lost with the recovery, cure or death of the host. Needs recording.	As permanent as the various media that carry the sign. Record usually made in some computer system.	As permanent as the various media that carry the sign. Record usually made in some computer system.	As permanent as the medium of the documentation carrying the sign.

TABLE II. DECONSTRUCTING THE CONCEPT OF 'TRACK' IN THE DISCIPLINES (SEE SECTION VI TO COMPARE 'TRACK' IN SSE)

Factor	Animal Tracking	Art Provenance	Epidemiology	Food Traceability	Luggage Handling	Metrology
Cause of track generation	The movement of the animal in space and time.	The transfer of ownership or location of the work of art.	The replication or mutation of the pathogen, and the infection of a new host.	The subdivision or amalgamation of the food product.	The movement of an item of luggage in space and time.	Steps in assuring standards conformity in measurement results, one instrument used to calibrate another.
Track maker	The individual animal.	Multiple people creating documentation associated with the same work of art.	Multiple people or animals with symptoms of the same disease.	Multiple people or systems creating and interacting with the codes associated with the food product along the food chain.	Multiple people or systems creating and interacting with the code associated with the item of luggage.	Multiple people documenting measurement procedures, their results and instrument calibrations.
Track represents	The forward path of an individual animal.	The path of ownership of a work of art from its original creator to its current owner or location.	The proliferation of a pathogen type, being the spread of disease from the source or an index case.	All the steps in the supply and distribution of a food product from source to consumption.	Both the intended and actual forward path of an item of luggage.	The chain of calibrations that anchors a particular measurement result in a reference standard.
Pattern of track	Linear.	Linear.	Linear, tree / hierarchy, star, network, etc.	Linear, tree / hierarchy, star, network, etc.	Two linear tracks (intended and actual).	Linear or tree / hierarchy.
Origin of track	The earliest sign identified (not necessarily the first sign made by the animal).	A sign establishing the creator of the work of art.	The source of the disease (or index case as proxy).	The source of the food product.	The departure airport.	The final measurement result.
Destination of track	The found animal (or the last sign made by the animal).	A sign establishing the current owner or location of the work of art.	The many potential end points in the spread of the disease.	The many potential points of consumption for the food product.	The ultimate arrival airport.	An SI unit or other internationally or nationally agreed reference standard.
Permanence of track	As permanent as its individual signs may remain in the environment.	As permanent as the media carrying the individual signs. A record of the entire track eases track reuse (a provenance claim).	As permanent as its individual signs may remain in the hosts. A record of the track is needed for continued use.	The signs of the track are usually recorded in the systems along the food chain, for some specified time period, easing reuse.	The signs of the track are usually recorded in a luggage handling system, for some specified time period, easing reuse.	As permanent as the media carrying the individual signs. A record of the entire track eases track reuse (a traceability claim).

TABLE III. DECONSTRUCTING THE CONCEPT OF 'TRACE' IN THE DISCIPLINES (SEE SECTION VI TO COMPARE 'TRACE' IN SSE)

Factor	Animal Tracking	Art Provenance	Epidemiology	Food Traceability	Luggage Handling	Metrology
Trace objective	To identify and find an animal.	To identify and establish the origin of a work of art.	To determine the potential spread of a disease. Also, to identify its source.	To render visible the supply and distribution chain of a food product.	To ensure the delivery of luggage. Also, to facilitate the retrieval of luggage.	To enable dependable, repeatable and interchangeable measures.
Direction of trace	Forwards with the animal for trace objective, following track direction.	Backwards through transfers of the work of art for trace objective, reversing track direction.	Forwards with the pathogen for trace objective, following track direction. Also, backwards to identify the pathogen's source, reversing track direction.	Following the track in both directions, forwards and backwards, is equally fundamental to the trace objective.	Forwards with the item of luggage for trace objective, following track direction. Equally so for luggage retrieval.	Forwards to the reference standard, following track direction. (Note that metrology refers to 'tracing back' to the reference from the measurement result.)
Trace maker	The tracker (i.e., hunter), usually one person, identifying and following the track.	Persons seeking to establish the provenance of a work of art (e.g., art historians, auctioneers, acquisition museums, buyers and sellers, etc.)	Epidemiologists and associated persons seeking to map the spread of a disease.	Persons making claims for a food product and its safety (e.g., food manufacturers and distributers). Accreditation may be required.	Airline and airport personnel seeking to retrieve luggage.	Persons providing measurement results make a claim of metrological traceability, or a third-party. Accreditation may be required.
Trace user	The tracker, following the track to pursue the animal.	Persons seeking to establish or authenticate the provenance of a work of art.	Epidemiologists and associated persons seeking to understand the spread of a disease and to design control measures.	Persons making and checking claims for food, or planning and undertaking a recall (e.g., government agencies).	Airline and airport personnel performing luggage retrieval tasks.	Persons using measurement results assess the validity of the claim of metrological traceability, and various accreditation bodies.
Trace beneficiary	The tracker and others (for food); animal owner (for pets); animal scientists (for behavior).	The current or potential future owner of a work of art (for valuation); society (for cultural preservation).	The local (epidemics) or global (pandemics) population (for control of disease and safety).	All parties involved in the supply and distribution of food (for economics); consumer (for safety).	The luggage owner (for service); airline industry (for economics); society (for safety).	Those domains and industries that rely on standard measures (for economics and safety).
Trace process	A track pursuit drill [5].	No process as such, depending upon heuristics. Simple guidelines have recently been promoted for recording provenance data [15].	Common steps to perform in a systematic outbreak investigation [1], and national and international guidelines to respond to particular emergency outbreaks (e.g., [6]).	No end-to-end responsibility for food traceability, but simple generic principles to distribute responsibility (e.g., those specified in EC178/2002 [9], including 'one up / one down' traceability [4]).	An international framework for tracing that revolves around use of a shared tracing and management system [10]. Individual airlines and airports have flexibility on their precise systems and implementation details.	Documenting the relationship of a measurement result to a 'higher authority' [12], time-stamping when used for calibration, recording the measurement procedure, its result and the associated uncertainty.
Aids to tracing	A field book of animal track types.	Examples of successful heuristics in provenance creation, suggesting possible documentary evidence relevant to the type of work of art or particular period.	Techniques and procedures for data collection, mining and fusion. Data visualizations, and statistical and mathematical modelling and simulations for analysis.	International codes and policies for making signs, along with increasingly sophisticated ways to 'label' and register the movement of food.	International codes and policies for making signs, along with increasingly sophisticated ways to 'label' and register the movement of luggage.	International initiatives for worldwide metrological traceability [3], a shared vocabulary [11] and visual aids to show the transfer of traceability at steps in a measurement process [8].
Impact of gaps on tracing	Gaps do not prevent a trace. They can often be overcome by backtracking or using alternative signs.	Gaps present a loss of traceability. They have the potential to be filled at a future time if new signs materialize.	Gaps can often be bridged, based on typical patterns of spread for known diseases and probabilistic models.	Gaps break the food traceability, but one up / one down records should regain it. DNA can trace the product, but not provide for process traceability.	Gaps can be overcome by exhaustive search for the item of luggage from its last known location and its known intended track.	Gaps break the metrological traceability.
Permanence of trace	The track can be traced many times while available, but the potential to trace eventually disappears. Tracing may be a one time activity if the tracker obliterates the tracks in making the trace. The value of the trace may disappear with the quarry.	The potential to trace remains while the track is available. The track can be recorded to ease future tracing and remain relevant indefinitely. However, the validity of a trace can become questioned with the discovery of new evidence.	The potential to trace remains while the track is available, which is transient. A record of the track is needed for tracing over time.	The potential to trace remains while the track is available. The signs or the full track are usually recorded to ease future tracing, but the useful life of a trace may diminish. Such records may be archived long-term.	The potential to trace remains while the track is available. The signs or the full track are usually recorded to ease future tracing, but the useful life of a trace may diminish. Such records are rarely archived long-term.	The potential to trace remains while there is a claim of metrological traceability. However, the uncertainty of a measure that a process or instrument provides changes, so the trace can be voided. Instruments need periodic re-calibration to retain it.