

An Advanced Digital Twin Approach for Iconographic Heritage Modeling and Processing

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Abstract

While the concept of the Digital Twin is gaining traction in Cultural Heritage (CH), its application is often limited to static "digital replicas," failing to capture the rich semantic and symbolic dimensions of heritage objects. A significant gap exists in formally modeling the complex, dynamic narratives inherent in CH entities in a machine-actionable way. This paper addresses this gap by introducing "Digital Cultural Heritage Twins" - autonomous, richly structured digital entities built using the Narrative Knowledge Representation Language (NKRL). Our approach employs an "augmented n-ary" framework to formally represent complex events, relationships, and abstract notions with a high degree of semantic precision. We demonstrate the methodology through a detailed formal analysis of the "pentimenti" (artistic revisions) in a self-portrait by Anthony van Dyck. To our knowledge, this represents the first application of a deep knowledge representation model to the layered narrative of pentimenti, moving beyond visual documentation to create a truly computable semantic twin.

CCS Concepts

- **Information systems** → **Multimedia content creation**; •
- **Computing methodologies** → **Artificial intelligence**; •
- **Applied computing** → **Media arts, Document analysis**.

Keywords

Cultural Heritage, Digital Twins, Knowledge Representation, NKRL, Pentimenti Formal Analysis.

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1 Introduction

The concept of Digital Twin (DT), a *high-fidelity virtual representation of a physical object or system*, has become a transformative force in fields ranging from engineering, manufacturing, aerospace, and healthcare. The core premise – a dynamic, synchronized link between a physical entity and its digital counterpart – is used to simulate, optimize, and predict behavior, offering profound analytical capabilities [1, 2, 3, 4]. More recently, this paradigm has successively evolved to encompass not just physical data but also the complex semantic and symbolic aspects that define an entity, giving rise to the notion of “semantic digital twin” This evolution has been particularly pioneered in the Built Environment sector with the introduction of a Building Information Modelling (BIM), offering a very detailed digital representation of the buildings’ structures and of the different assembling construction phases involving then walls, pillars, floors, ceilings etc. [5, 6]. With this additional emphasis on the “semantics” of the digital twins, the need for the use of advanced knowledge representation techniques for their set-up is even more evident.

The interest in a possible use of digital twins, in their “semantic-based” versions in particular, has caught the attention of the Cultural Heritage (CH) community that has enthusiastically embraced this technical novelty. Initiatives like “European Collaborative Cloud for Cultural Heritage” (ECCCH) underscore this enthusiasm, with the ECCCH’s Report on a Collaborative Cloud for Cultural Heritage [7] advocating for the creation of Digital Twins and Digital Twins Repositories. The report, which represents the European Commission’s guide for the implementation of a cultural collaborative cloud, underlines that the creation of digital twins of heritage objects will allow us to move “... from fragmented and episodic digitisations to ‘permanent’ digital counterparts of heritage objects, able to progressively integrate new data acquisitions, analysis, and enrichment ...” (page 30). Moreover, given that “... The CH domain lacks a European Collaborative Cloud for storing, accessing, using and documenting digital twins ...” (page 66), “... the ECCCH must offer a repository for the on-line archive of digital twins”, where these twins should represent “... enriched digital models including data, metadata and provenance” (page 67). These Digital Twins aim to enhance access, documentation, and interaction with CH entities, such as iconographic narratives (e.g., paintings, sculptures, and mosaic), which convey complex visual messages.

Despite this enthusiasm, the literature reveals a knowledge gap in the implementation of Digital Twins for CH. Current approaches often equate Digital Twins with "digital replicas," which are typically high-fidelity but static 2D or 3D representations created using techniques like digital imaging, photogrammetry, and laser scanning [8, 9]. These replicas excel at capturing an object's visual and physical characteristics but fail to represent the semantic, cultural, and historical dimensions of CH entities. Systems like CIDOC CRM [10] provide robust frameworks for museum documentation but are limited by their static, binary structures, which cannot model dynamic, n-ary relationships such as temporal sequences or causal interactions inherent in CH narratives [11]. Similarly, Semantic Web approaches, such as Resource Description Framework (RDF)-based ontologies, struggle to handle complex, multi-argument structures [12]. This gap hinders the creation of fully machine-actionable Digital Twins capable of representing nuanced semantic aspects. Furthermore, from an implementation perspective, the appropriate structural definition that should be practically associated with the concept of DT within the context of ECCCH is, at present, *far from being unequivocally established*. This is further evidenced by examining the already funded projects, such as ECHOES (<https://www.echoes-eccch.eu/>) and HERITALISE (<https://heritalise-eccch.eu/>), which aim at developing the ECCCH platform.

This paper addresses this gap by proposing "Digital Cultural Heritage Twins," autonomous, richly structured digital entities built using the Narrative Knowledge Representation Language (NKRL) [13] and characterized by the following properties:

- According to the original definition of digital twins as *virtual/digital image of a real-world entity*, our Digital CH Twins correspond to *powerful, structured, full-fledged autonomous digital entities*, able to be independently stored on a CS (Computer/Cloud System) platform and directly exploitable on this platform.
- Thanks to the use of an advanced Knowledge Representation system like NKRL capable, among others, of *directly representing and dealing with difficult abstract notions* like temporal information, sentiments, behaviors, opinions, mutual relationships etc., they are *totally machine actionable*, represented in an entirely *formal/digital way* without any need to resort, e.g., in a schema.org style, to possible *natural language descriptions*.
- They are expressly created according to the *specific wishes/instructions/requirements of CH professional* interested in representing in digital format the most important, mainly *semantic/conceptual aspects*, of the original CH entities/situations. These CH professionals will have also *the final say* on the endorsement of the results derived from the Digital CH Twins' use.

Successful applications of the above principles have already been realized in a particularly important, both from a quantitative and qualitative point of view, Cultural Heritage domain, the so-called "*Iconographic Narratives*" field. The iconographic narrative entities correspond to paintings, drawings, frescoes, sculptures, bas/high-reliefs, tapestries, mosaics, etc. but also, more in general,

to photographs, posters, comics, cartoons, billboards. Their aim is the transmission to the user/observer of a particular *visual message* making use only of *graphical/illustrative modalities*. The effectiveness of these principles for modeling complex iconographic narratives has been demonstrated in previous research [11, 14, 15]. In the present study we present a detailed case study centred on the formal analysis of "pentimenti"(artistic revisions), a topic whose layered, evolutionary nature poses a significant challenge for traditional digitalization methods. We construct a complete Digital CH Twin of the series of changes within a self-portrait by Anthony van Dyck, using this example to illustrate how our NKRL-based system can effectively model the dynamic relationships and semantic nuances that define such a complex work of art.

In this work, we interpret Digital Twins within the Cultural Heritage context primarily as semantic/narrative digital counterparts rather than as real-time predictive systems. We acknowledge that our proposal does not include features such as live data synchronization, predictive simulation, or closed-loop control-characteristics typically associated with industrial DTs. Instead, our focus lies in the enrichment of the digital counterpart with machine-actionable semantic structures that allow CH professionals to model, query, and analyze complex iconographic narratives. This positioning aligns our work with the recent spectrum of semantic/narrative digital twins [17, 18], while contributing a novel NKRL-based approach designed to overcome the representational limits of binary models like RDF and CIDOC CRM.

In the following, Section 2 presents a quick analysis of the present uncertain research situation in the Digital Cultural Heritage Twins domain and of the associated "expressiveness" problems. This last are (at least partly) resolvable, in our opinion, through a radical change from "binary" to "n-ary" of the knowledge representation systems used to implement the Digital CH Twins. Section 3 illustrates the main characteristics of the n-ary Knowledge Representation system, NKRL, chosen for the implementation of our version of the Digital CH Twins. Section 4 shows how NKRL allows the realization of a complete formal analysis (of a complete Digital CH Twin) of a series of "pentimenti" concerning a Van Dyck's self-portrait. Section 5 is a short "Conclusion" of the paper.

2 Some reflections about the "State of the Art"

The situation of uncertainty about the real nature of the Digital Cultural Heritage Twins notion that characterizes, at least at the moment, the ECCCH domain is, in reality, far more serious than it can seem at first glance, and concerns also the proper "*inner meaning*" of this notion. As already stated in fact, very often "digital twin" is understood as a simple synonymous of "*digital replica*" – "digital replica" [16] should only concern the three-dimensional acquisition and reconstruction methods that make use of photogrammetry and laser scanning techniques to capture the structural characteristics of physical cultural heritage objects, in an architectural context for example. This specific misleading interpretation of the Digital Cultural Heritage Twin notion can be considered as particularly dangerous given that, among other

things, it precludes any possibility of modeling the “semantic/immaterial/non-visible” aspects (in the most general meaning of these words) of the CH entities with their cultural, historical and social contexts.

Returning now to more acceptable forms of definition, we can note that some recent papers [17, 18] produced in a generic ECCCH context can suggest that ECCCH researchers are (possibly) moving in a direction *quite divergent with respect to the original, highly dynamic origin, of the Digital Twins concept*. The twins described in the two papers above appear, in fact, as *purely static kind of “description maps”* denoting the possible recognition within the original CH entities – a portrait and a monastery building in [18] – of *descriptive elements/keywords/metadata etc.* like “building”, “document”, “painting”, “manuscript”, “church”, “wall frescoes” etc. relied by simple binary relationships like “is documented in”, “was observed by”, “is concluded that”, “was premise for” etc. This sort of “twins” can be *surely useful in a “documentary/information retrieval” context according to a CIDOC CRM [19] style*, but surely not in any possible form of “dynamic simulation and testing” use *as expected according to the original Digital Twin conception*.

CIDOC CRM is a very powerful and popular system that, since December 9, 2006, is also the official standard ISO 21127:2006, and which seems to be considered at present as *an absolutely necessary component of any possible digitalization effort in the Cultural Heritage domain*. Its practical utility for structuring in a coherent and rational way, along with its multiple extensions (see <https://site2024.cidoc-crm.org/collaborations>), the terminological, documentary, information retrieval-oriented knowledge absolutely needed for developing real world applications in the Cultural Heritage domain, *cannot in no way be discussed*. It cannot be considered, however, as a real knowledge representation system because of its information retrieval/documentary roots, implying then a basically static vision of the world.

It can be considered, in fact, as the peak of a long-term endeavor to produce *advanced museum documentation in digital form*. This work begun in the sixties with the adaption, for cataloguing and information retrieval tasks, of “thesauri” like ICONCLASS, ULAN, and AAT, see [14] in this context for example. An essential step of this production process has been the creation (1995) of the “Dublin Core system” [20], developed originally as a *metadata system* for describing in a simple and standardized way any sort of documentary resources and interpreted also, then, as a *really basic knowledge representation system*. It made use, in fact, of elementary knowledge representation categories like subject, title, author, publisher etc. A more sophisticated model was the VRA Core 4 XML Schema [21], produced as Beta version in 2005 and as full version in 2007. Concrete work on CIDOC CRM started in 1996, *by restructuring the pre-existing, metadata-oriented museum documentation into a full ontology*, capable of providing formal definitions for describing the main implicit and explicit concepts and relationships actually used in museum documentation. In its March 2021 version [19], the ontology includes more than 150 entities (classes, concepts) from E1: “CRM Entity” to E95:

“Spacetime Primitive” and more than 170 properties. However, even if a notion like, e.g., “E5 Event” is actually included in the CIDOC CRM ontology – as “Subclass of E4 Period”, “Superclass of E7 Activity, E63 Beginning of Existence, E64 End of Existence”, and having as concrete example, among others, “The Yalta Conference” and “The battle of Stalingrad – *no structured description of this notion is concretely supplied*. This means that the general semantic categories proper to the “event” notion, like the role of the characters involved with respect to the general framework of the specific event, their mutual relationships, their cardinality, enumeration, alternativity, specification characteristics, the Causal, Goal, Condition... relationships of the event with respect to the other ones, the general context, etc. *are not identified/described*. We can remark, in contrast, the structured and detailed logico-semantic description of the events/states/actions... proper to NKRL, the Narrative Knowledge Representation Language, see the next Section.

Eventually, from an implementation point of view and in conformity with its terminological/taxonomic/Linnaean origin, we can note that CIDOC CRM *follows a sort of quite rigid “binary system” approach*. It is subjected then to all the serious shortcoming problems, from an “expressiveness” point of view, proper to this sort of systems see also, e.g., the (strictly binary too) RDF graphs-based Semantic Web (SW) approach. By the way, CIDOC CRM and all the compatible systems mentioned above are provided with SW-RDF compatible versions see, e.g., the DCMI (Dublin Core Metadata Initiative) Abstract Model [22] or the RDF(S) versions of the CIDOC CRM tool [23]. In the CIDOC case, the expressiveness problems are even worsened by the fact of *being used into a not formalized domain as the Cultural Heritage one*, characterized by the presence of “unusual” notions and expressions denoting, e.g., sentiments, behaviors, influences, attitudes, reactions, feelings, etc.

In a binary approach, as its name indicates, the number of arguments that can be associated with a given predicate/property is limited to two (two-place relations): the general format of the RDF “triples” can be formulated, then, as simple relationships of the type “entity1 – property – entity2/value”. This format can be useful to associate people’s names with numeric strings using the property `phoneNumber`, or to characterize the sky has having the color blue via the property `hasColour` without, however, *proposing general solutions* able to deal with the countless *n*-ary structures commonly used in everyday life, see a ternary relation like “recommend”, `Recommend (Teacher, Book, Class)` or an *n*-ary one like “purchase”, `Purchase (Seller, Buyer, Good, Price, Date...)` and so on – the degree of a relation corresponds to the number of the associated arguments. These obvious remarks explain the popularity of *a set of new proposals of n-ary knowledge representation systems* that make reference, mainly, to the so-called “Davidson Hypothesis” see, e.g., [24, 25, 26, 27]. Derived from a Davidson’s paper about the formal representation of events published originally in 1967 [28] and then revised in 1980, this hypothesis states generically, in its common formulation (see, e.g., [27]) that, “An *n*-ary relation can be expressed as a sequence of binary relations between its arguments”. In their 1979 CACM paper [30], Deliyanni and Kowalski had already, on their part,

more concretely asserted that, “Every n -argument (n -ary) relationship can be re-expressed as a conjunction of two-argument (binary) relationships. If $n > 2$, $n + 1$ binary relationships are needed. If $n = 1$, then only one is necessary” [30, p. 186]. This last paper is particularly significant from the point of view of the conception of a concretely useful n -ary representation language *given the importance attributed by the two Authors to the notion of “role” in the associated examples*. The presence of this notion in the formal rendering of the n -ary structure is quite necessary given that, as shown by the above example of an n -ary situation like “purchase”, these complex structures usually involve the simultaneous presence of several actors/entities (Seller, Buyer, Good, Price, Date...), with each of them endowed with a specific “function/role” in the context of the situation, (event, action etc.) denoted by the specific structure.

Many of the new n -ary proposals introduced above are, anyway, *highly theoretical* and then, at least partly, “incomplete” from a practical applications point of view. See, e.g., the frequent absence of any formal expression of the modalities according to which the sentiments, behaviors, influences, attitudes, reactions, feelings, etc. are expressed, the lack of a complete and faithfully reproduction of the temporal information and of any possibility of taking into account important relationships like coordination, enumeration and alternative, the absence of the modalities to be used for linking together several n -ary expressions and build up composite structures as complex events, episodes, narratives, etc. This is why NKRL has been chosen as support for the creation of the Digital CH Twins: an “augmented” n -ary system provided with (actually implemented) solutions for the above problems.

Recent projects within the ECCCH ecosystem and related initiatives have begun to explore semantic enrichment of cultural heritage twins. The Heritage Digital Twin ontology and its sensor-oriented extensions [15, 17, 18] highlight an increasing awareness of the need to go beyond static replicas toward diachronic, semantically structured representations. However, these approaches often remain bound to metadata annotation and CIDOC CRM-style binary relations. Our work diverges by embedding a fully formalized augmented n -ary framework that can directly model temporal development, causal links, and semantic nuances such as intentions, roles, or affective states. In this sense, our proposal complements existing CH digital twin efforts, positioning NKRL-based Digital Twins as a layer for deep semantic representation and reasoning.

3 Basic information about NKRL

NKRL is, at the same time, a high-level, formalized representation of the deep-meaning of any sort of those so pervasive “narrative-like” descriptions (textual, oral, iconographic, photographic, cinematographic, advertising and so on) and a complete computer-science environment (developed in Java) for creating and concretely using this sort of representations. From an ontological point of view, *its most important feature concerns the utilization of two quite different with respect to their implementation/use but strictly integrated ontologies*.

A first ontology – HClass, hierarchy of classes [13, pp. 43–55, pp. 103–137], theoretically equivalent to the CIDOC CRM

ontology discussed above – *concerns the representation of that terminological/documentary “static” knowledge, see also the previous Section, necessarily involved in the construction/representation of any sort of narratives*. It includes presently (July 2025) more than 7,500 “standard” concepts – standard meaning here that the “properties” or “attributes” used to define a given concept are simply expressed as binary (i.e., linking only two arguments) relationships of the “property/value” type, see above. From a purely formal point of view HClass is not fundamentally different, then, from the ontologies built up using the frame version of Protégé. In spite of its apparent simplicity, *HClass is absolutely indispensable for the correct functioning of NKRL* – for example, all the validity checks concerning the values retrieved by the NKRL inference rules involve necessarily the exploration of HClass. Moreover, from a strict ontological point of view, HClass introduces *interesting solutions for the formal representation of controversial entities like, e.g., substance_ and colour_*.

Arguably, the most innovative ontological feature of NKRL is the ontology of elementary events/situations, a hierarchically-oriented structures represented by (about 150) n -ary knowledge patterns, very easy to generalize and customize. These patterns are called “*templates*” in an NKRL context, and the whole ontology is denoted as HTemp, the hierarchy of templates. Templates describe formally general classes of elementary events/situations like “have a specific attitude towards someone/something”, “move to a given place”, “send a message to someone”, “being characterized by a given property”, “*face* a negative situation”, etc.

Templates are represented according to an “*augmented n -ary approach*” (see above) formalized as in Eq. 1:

$$(L_i (P_j (R_1, a_1) (R_2, a_2) \dots (R_n, a_n))) \quad (1).$$

To ensure clarity and computational tractability, NKRL adopts a primitive vocabulary of seven predicates (e.g., BEHAVE, EXIST, PRODUCE) and seven functional roles (e.g., SUBJ, OBJ, SOURCE, CONTEXT). These primitives act as building blocks that can be combined to describe complex events while avoiding combinatorial explosion or inconsistencies.

Each template is uniquely identified by a symbolic label (L_i) that links together its predicative occurrences into coherent structures. Arguments (a_k) filling the roles are drawn from the companion HClass ontology, ensuring semantic consistency. In addition to simple terms, NKRL supports expansions (e.g., alternative, coordination, enumeration, specification lists), which increase its expressive power for representing nuanced or multi-faceted situations.

The result is an augmented n -ary representation that captures not only who does what to whom, but also contextual information such as time, modality, or attitudes. For example, a purchase can be modelled in a single formal structure linking seller, buyer, object, price, and date, rather than being fragmented into binary triples. This ability to encode complete events as self-contained units is what enables NKRL to represent the layered, evolving narratives typical of Cultural Heritage objects.

As a first very simple example of the NKRL formalism, we show now in Table 1 how to build up *predicative occurrences from specific templates*, a very important and frequent operation in an NKRL context

Table 1. Deriving a predicative occurrence from a template.

```

name: Move:TransferMaterialThingsToSomeone
father: Move:TransferToSomeone
position: 4.21
natural language description: "Transfer a Material Thing to
Someone"

MOVE:
  SUBJ: var1: [var2]
  OBJ: var3
  [SOURCE: var4: [var5]]
  BENF: var6: [var7]
  [MODAL: var8]
  [TOPIC: var9]
  [CONTEXT: var10]
  { [modulators], #abs }

var1: human_being_or_social_body; var3: artefact_; var4:
human_being_or_social_body; var6: human_being_or_social_body;
var8: activity_related_property, process_, service_; var9: sortal_concept;
var10: situation_, symbolic_label; var2, var5, var7: location_

ex.c1: MOVE:
  SUBJ: PETER_
  OBJ: ART_BOOK_1
  BENF: MARY_
  MODAL: as_a_gift
  date-1: 2018-12-28
  date-2:

```

This example concerns the *formal encoding* (the construction of the corresponding *specific Digital CH Twin*) of the very simple event, “Peter has given an art book to Mary as a gift”; this event corresponds, in particular, to one of the examples listed in the Deliyanni/Kowalski paper [30]. As we can see from Table 1, in a template the arguments of the *predicate* (the a_k terms in Eq. 1) are *actually represented* by “typed variables” (var_i) with associated constraints. These last are expressed as concepts or combinations of concepts, i.e., using elements of the HClass ontology – this confirms that the two NKRL’s ontologies work in a *strictly connected way*. When creating a predicative occurrence as an instance of a given template, the constraints associated the variables are used to specify *the legal sets of HClass terms, concepts or individuals, that can be substituted for these variables within the occurrence*. For example, in Table 1, we must verify that PETER_ and MARY_ are true HClass instances of individual_person, a specific term of human_being_or_social_body, see the constraints on the SUBJ and BENF roles of the Table 1 template. The individual ART_BOOK_1 is an instance of the art_book concept, specific term, through intermediate steps, of artefact_, see the constraint on OBJ in Table 1. as_a_gift is a specific term of activity_related_property, included in the qualifier_ sub-tree of HClass.

Setting up really complete and expressive Digital CH Twins expressed in NKRL format implies, in many cases, to make use of

the possibilities offered by the language for connecting together different predicative occurrences in the context of complex episodes, scripts, storyboards, narratives etc. This requires the use of NKRL-specific, second-order conceptual structures. In this context, we can mention first the so-called *completive construction*, a particularly powerful Knowledge Representation tool that offers the possibility to refer to an elementary event as an argument of another event see e.g., below, the #vand.c4 example of Table 1. This type of structure is largely used in NKRL to represent, e.g., any possible sort of transmission of an information. Another, more general kind of second-order structure allows us to set-up coherent sets of elementary events by associating together, through several kinds of formalized connectivity operators, the NKRL representations of independent elementary or complex events. This mechanism is called *binding occurrences*, and it is implemented under the form of *lists* including a binding operator Bn_i and its L_i (see Eq. 1) arguments:

$$(Lb_k (Bn_i L_1, L_2 \dots L_n)) \quad (2)$$

where Lb_k is the symbolic label identifying the global binding structure. The Bn_j operators are: ALTERN(ative), COORD(ination), ENUM(eration), CAUSE, REFER(ence), the *weak causality operator*, GOAL, MOTIV(ation), the *weak intentionality operator*, COND(ition). These structures are particularly important given that, when the NKRL formalization of a complex situation/episode implies the setting-up of a composite Digital CH Twin including both simple predicative occurrences and second-order conceptual structures, *the top-level occurrence introducing the full representation has necessarily the form of a binding occurrence in the Eq. 2 style*, see again next Section.

Query and inference procedures are particularly important within a general NKRL/Digital CH Twins context and are described in detail for example in [32]. Querying/reasoning in NKRL ranges from the *direct questioning* of an NKRL knowledge base (KB) making use of search patterns p_i that unifies information in the base by means of a (semantic-expansion grounded) *Filtering Unification Module (Fum)*, to *high-level inference procedures* managed by a powerful InferenceEngine based on a *Prolog-like backward-chaining with chronological backtracking approach*, see [13, pp. 183-243]. These procedures concern *mainly two classes of rules, transformations and hypotheses*. Transformation rules try to adapt a search pattern p_i that failed (that was unable to find a unification within the KB) to the contents of this base using a sort of analogical reasoning, while the hypothesis rules allow us to create a causal explanation of an event (a predicative occurrence c_j) retrieved using a given p_i .

In our context, the novelty of the study lies not in the NKRL language itself but in its application to Cultural Heritage Digital Twins, where it enables the computable modeling of iconographic narratives. Furthermore, while NKRL offers deeper expressiveness than binary models, it can be aligned with CIDOC CRM concepts via its HClass ontology, ensuring compatibility with CH documentation standards.

4 A concrete example

Paintings are more than can be seen with the naked eye as under their surface *remnants of intermediate concepts and sketches of entire paintings* can be hidden. Terms like “underdrawings/underpaintings” were used to sketch the initial design of a painting with charcoal or paint and, if this initial concept was changed during the execution of the painting, the unwanted features were covered by paint and became a “*Pentimenti*” (an Italian term for “regrets”). Finished or quite finished paintings were at times covered – in general to reuse the support panel – with another painting often dealing with a completely different subject.

These hidden features became accessible in the last years due to progress in imaging techniques, such as X-Ray Radiography (XRR), Infrared Reflectography (IRR), scanning MAcroscopic X-Ray Fluorescence spectroscopy (MA-XRF) and Reflectance Imaging Spectroscopy. Note that, in conformity with the general semantic/conceptual orientation of this paper (Digital Cultural Heritage Twins), what represents the main interest in this text is not an *in-depth account of the specific techniques used to reveal specific pentimenti*, but the accurate description in digital terms of the *different, successive steps leading to the final result*.

The case study taken into account here concerns the reproduction in digital form of the results obtained in the framework of the *multidisciplinary analysis of a portrait* – about 1616/17, panel, 36.5 × 25.8 cm., on display in the Rubenshuis, Antwerp – alternatively attributed to Peter Paul Rubens and to his pupil Anthony van Dyck [33]. Several *high-end technological methods*, such as X-radiography, X-ray computer tomography, mammographic tomosynthesis and macroscopic X-ray fluorescence, have been employed in this context revealing the existence of a number of “*pentimenti*”. They have been ascribed, by the team in charge of this work, to a *rather immature hand*, which makes the authorship of Peter Paul Rubens very unlikely. Eventually, what emerges is a portrait of an *ambitious young man* with a luxuriant head of hair and a slightly turned-up collar (a “cloak”), added later with a hat as a result of several “*pentimenti*”. The final facial features and the execution of details like the bold curls’ points undeniably, according to the research team, in the direction of Anthony van Dyck as the author of his own portrait.

Fig. 1 visually highlights what expounded above showing, a) a photograph of the final work, b) a “copper distribution” image that corresponds to the presence of green and blue copper-based pigments (azurite, malachite and their synthetic analogs) and c) the “lead distribution” image that is dominated by the distribution of lead white, see again [33]. In Fig. 1b, the copper distribution, we can remark the originally simpler vestment that was later overpainted with the cloak. In the lead distribution, Fig. 1c, additional pentimenti can be noticed. In this intermediate stage, in fact, the sitter was not wearing a hat, but had open hair; furthermore, his face was rounder, which was corrected for the final version. Finally, a smaller, more modest collar appears the final version, Fig. 1a.

A (simplified) formal representation of the different phases the Van Dyck’s self-portrait went through thanks to several “*pentimenti*”, Fig. 1, is reproduced in NKRL format in Table 2.

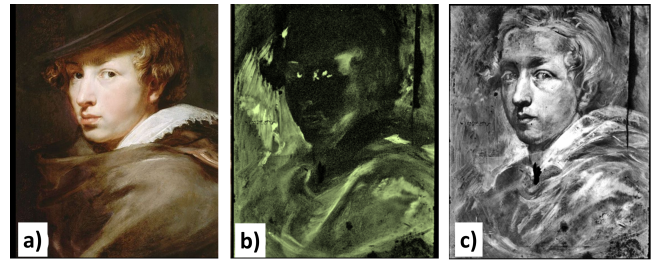


Figure 1: Anthony van Dyck, Self-portrait, c. 1616/17, panel, 36.5 × 25.8 cm. Antwerp, Rubenshuis. As photograph (a), copper distribution image (b) and lead distribution image (c), acquired by macroscopic XRF. In the latter images, a brighter tone indicates a higher abundance of this chemical element. Adapted from: K. Van der Stighelen, *et al.*, “Young Anthony van Dyck revisited: a multidisciplinary approach to a portrait once attributed to Peter Paul Rubens”, *ArtMatters* 2014, 6, 21-35.

Table 2. NKRL-like representation of the Van Dyck’s self-portrait issue

vand.c1: (COORD vand.c2 vand.c3 #vand.c4)

As already stated in Section 3, the final Digital Twin associated with a given Cultural Heritage item is necessarily in the form of an NKRL “binding structure”. In the Van Dyck’s case, the binding structure, vand.c1, includes two components. The first, vand.c2, describes the creation of the self-portrait and some of its “physical” characteristics. The second component, vand.c3, informs us that a group of researchers has published an academic paper where they uncover (see #vand.c4, completive construction) the results of an in-depth scientific examination of the self-portrait making use, among other things, of X-ray computed tomography, XRF imaging and mammographic tomosynthesis. This study has then shown that, because of the “pentimenti” introduced by Van Dyck, the self-portrait went through three phases, succinctly described here.

vand.c2: (COORD vand.c5 vand.c6)

The first component of the structured metadata representation consists of two predicative occurrences.

vand.c5: PRODUCE:
 SUBJ: ANTHONY_VAN_DYCK: (ANTWERP_)
 OBJ: PAINTING_3
 TOPIC: (SPECIF self_portrait ANTHONY_VAN_DYCK)
 date-1: (1/1/1616, 31/12/1617)
 date-2:

Produce:Entity (6.2)

A painting (conventionally: PAINTING_3) concerning its own self-portrait, has been produced by Anthony Van Dyck in the (supposed) temporal interval 1616-1617.

vand.c6: OWN:
 SUBJ: PAINTING_3: (ANTWERP_RUBENSHUIS)
 OBJ: property_
 TOPIC: (COORD1 oil_on_panel (SPECIF dimension_

(SPECIF centimetre_ (36.5 25.8)))
 { obs }
 date-1: today_
 date-2:

Own:CompoundProperty (5.42)

We can remark today (temporal modulator obs(erve)) that PAINTING_3 i) is presently located in the Antwerp's Rubenshuis, and ii) that it consists of an oil-on-panel picture having a (36.5 x 25.8 cm.) size. The use in this predicative occurrence of "COORD1" instead of the usual "COORD" derives from the need for differentiating, in the NKRL's "external" format, the operator COORD(ination) when used, in this case for example, in a predicative occurrence context, from the same operator when used see, e.g., vand.c1 above, in a "binding occurrence" context.

vand.c3: MOVE:

SUBJ: (COORD1 KATLIJNE VAN_DER_STIGHELEN
 KOEN JANSENS GEERT VAN_DER_SNICKT
 MATTHIAS_ALFELD
 BEN VAN_BENEDEN BERT_DEMARSIN
 MARC_PROESMANS GUY_MARCHAL JORIS_DIK)
 OBJ: #vand.c4
 MODAL: (SPECIF SCIENTIFIC_PAPER_3 (SPECIF
 published_on ART_MATTERS_JOURNAL))
 date-1: 1/6/2014, 30/6/2014
 date-2:

Move:GenericInformation (4.41)

In June 2014, Katline Van der Stighelen and colleagues have diffused the information described in vand.c4 by means of a paper published in June 2024 on the "ArtMatters" Journal.

vand.c4: (COORD vand.c7 vand.c8)

The information spread by Katline Van der Stighelen and colleagues via their paper is formed of two parts.

vand.c7: (CAUSE vand.c9 vand.c10)

The first part tells us that the situation related in vand.c9 is caused by what described in the occurrences predicative vand.c10.

vand.c9: OWN:

SUBJ: (SPECIF artistic_creation PAINTING_3)
 OBJ: property_
 TOPIC: (COORD1 (SPECIF includes_ (SPECIF PHASE_1
 (SPECIF usually_denoted_as initial_))) (SPECIF
 includes_ (SPECIF PHASE_2 (SPECIF usually_
 denoted_as intermediate_))) (SPECIF includes_
 (SPECIF PHASE_3 (SPECIF usually_denoted_as
 final_)))
 { obs }
 date-1: 1/6/2014, 30/6/2014
 date-2:

Own:CompoundProperty (5.42)

The production of the self-portrait of Anthony Van Dyck is structured into three phases, conventionally denoted as initial phase, intermediate phase final, definitive phase; even if this specific temporal sequence cannot be precisely confirmed. usually_denoted_as is a specific term of general_characterising_property in HClass. Te construction of the TOPIC's filler is coherent with the "priority" rule, see the previous sub-sections, which regulates the set-up of the complex fillers and forbids, among other things, the use of COORD(ination) structures within SPECIF(ication) lists – but not the inverse.

vand.c10: PRODUCE:

SUBJ: ANTHONY_VAN_DYCK
 OBJ: (SPECIF pentimenti_subsequen8_ (SPECIF cardinality_
 several_))
 DEST: PAINTING_3

CONTEXT (SPECIF phased_production PAINTING_3)
 date-1: 1/1/1616, 31/12/1617
 date-2:

Produce: PerformTask/Activities (6.3)

The phased development of the picture is linked to the introduction by Van Dyck of repeated "pentimenti" into his self-portrait.

vand.c8: (COORD vand.c11 vand.c12 vand.c13)

The second part of the information spread by Katline Van der Stighelen and colleagues concerns the description of the changes made to the self-portrait within each phase.

vand.c11: (COORD vand.c14 vand.c15)

The amendments of PHASE_1 are described making use of two predicative occurrences.

vand.c14: EXPERIENCE:

SUBJ: (SPECIF image_support ANTHONY_VAN_DYCK):
 (PAINTING_3)
 OBJ: MODIFICATION_1
 SOURCE: ANTHONY_VAN_DICK
 MODAL: (SPECIF pentimenti_PHASE_1)
 CONTEXT: (temporal_development PHASE_1)
 date-1: 1/1/1616, 31/12/1617
 date-2:

Experience:ValuedSituation (3.2)

During the first phase, the self-portrait undergoes a set of changes represented by the individual MODIFICATION_1 – "modification" – pertains to the mutual_relationship HClass sub-hierarchy./

vand.c15: OWN:

SUBJ: MODIFICATION_1
 OBJ: property_
 TOPIC: (COORD1 open_hair (SPECIF wearing_ (SPECIF
 clothing_simple_)) (SPECIF not_wearing_hat_))
 { obs }
 date-1: today_
 date-2:

Own:CompoundProperty (5.42)

In agreement with the semantics of the Own:Simple/CompoundProperty templates, the changes to his own self-portrait introduced by Van Dyck in PHASE_1 are included in the filler of the TOPIC role.

vand.c12: OWN:

SUBJ: MODIFICATION_2
 OBJ: property_
 TOPIC: (COORD1 (SPECIF open_hair important_amount)
 (SPECIF face_ (SPECIF rotund_more_)) (SPECIF addition_
 (SPECIF ROUND_COLLAR_1 white_large_)))
 { obs }
 date-1: today_
 date-2:

Own:CompoundProperty (5.42)

The description of the changes in phase 2 and 3 follows the same schema used to illustrate the changes in phase 1: Van Dyck image undergoes some modifications (EXPERIENCE template in the style of vand.c14 above) and these modifications are described in an OWN + property_ template in the style of vand.c15 above. To avoid wasting space, only the predicative occurrences corresponding to the OWN + property_ template are reproduced below for phases 2 and 3.

vand.c13: OWN:

SUBJ: MODIFICATION_3
 OBJ: property_
 TOPIC: (COORD1 (SPECIF wearing_hat_) (SPECIF face_
 (SPECIF rotund_less_)) (SPECIF addition_ (SPECIF
 ROUND_COLLAR_1 (SPECIF size_reduced_)))
 { obs }
 date-1: today_
 date-2:

Own:CompoundProperty (5.42)

See the comment for the previous occurrence.

5 Conclusion

From a Computer Science perspective, NKRL is a fully implemented Java system that has been applied in numerous domains where data can be assimilated to “narrative information”: history, juridical and administrative documents, manufacturing processes, industrial incident reports, emotive situations, inappropriate internet content, and more. A recent industrial application concerned the mechanization of charging procedures for a bending machine at the Greek company Kleemann Hellas SA [34, 35].

Despite these applications, NKRL’s adoption has largely remained within experimental test cases in European projects. A commonly cited obstacle is the difficulty of working directly with the NKRL formalism (“metalanguage”), which requires managing entities such as predicates, roles, temporal markers, and operators. To address this, our next developments focus on using Generative AI to accelerate the creation of NKRL structures from natural language descriptions. While machine translation across natural languages is well advanced, research on automatic/semi-automatic translation from free natural language to formal knowledge representations is still scarce. Nonetheless, encouraging precedents exist in related domains such as NL-to-SQL translation [36].

This paper has introduced the concept of Digital Cultural Heritage Twins based on the Narrative Knowledge Representation Language (NKRL). We demonstrated how NKRL’s augmented n-ary formalism enables the modeling of complex, layered iconographic narratives - in this case, the pentimenti of Van Dyck’s self-portrait - going beyond the limits of static digital replicas and binary ontology models.

In summary, our contribution should be understood as advancing the semantic/narrative dimension of Digital Twins for Cultural Heritage, rather than replicating their real-time industrial functionalities. By situating NKRL as a semantic backbone, we provide a foundation for machine-actionable, richly structured Digital Twins that can support formal reasoning, semantic querying, and the computational exploration of cultural narratives.

We acknowledge important limitations: the current work is based on a single case study; no quantitative evaluation or large-scale validation has yet been performed; and features such as real-time data streams or predictive simulation, central to industrial DTs, are outside our scope. Addressing these aspects represents a direction for future research.

Looking ahead, we plan to extend this approach to a wider range of Cultural Heritage objects (e.g., sculptures, manuscripts, architectural elements) and to investigate methods for quantitative validation and user evaluation. A further challenge is usability: NKRL requires expertise in formal modeling, which we propose to mitigate through AI-assisted NL-to-NKRL translation. Finally, interoperability with existing standards such as CIDOC CRM and Linked Open Data frameworks remains an important

avenue: we envision NKRL acting as a complementary deep semantic layer, aligned with current efforts on semantic heritage twins [17, 18]. Through these extensions, NKRL-based Digital Twins have the potential to become a key infrastructure for capturing, preserving, and computationally analyzing the rich semantic fabric of cultural heritage.

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