Modeling the Resituation of Memory in Neurobiology and Narrative

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Abstract

In narrative and neurobiological processes, a common response to an unexpected event can be observed: retroactive reinterpretation. In this activity, an established state of knowledge is restructured so that its ability to interpret causal consequences changes. We present a new graphical knowledge modeling technique to track the stages of retroactive reinterpretation in both narrative and biological domains. This method is based on situation-theoretic foundations, which have been extended using narrative devices to capture elusive properties of everyday reasoning, such as context and causal anticipation. The method and its accompanying visual model enables us to experiment with representational reasoning about cause, shifts in influence between distinct systems and implicit knowledge. This work-in-progress indicates that cross-system, multi-ontology intelligence processes can be modeled using narrative mechanisms. A future goal is to use this method to address problems in ontological interoperability for predictive, multi-system neurobiological modeling. Capturing implicit causal agency in biology using a narrative-based model is thus feasible but comes with challenges in graphical display, which are discussed.

Introduction

An elusive goal is to model causal reasoning in an open world, especially when interpreting unexpected events and implicit information (Devlin, 2009). One problem is the nuance of real-world context, and the way the generality of an ontological reference framework struggles to account for it. Another problem concerns the way such interpretation must change as a real-world situation evolves (Sowa, 2010). To model how contextual information is captured and modified, we use a formal system based on narrative structure. Stories are composed of semantic transitions between states – changes of scene, perspective and ideas (Herman, 2009). These transitions employ multiple frames of reference, which overlap like stepping stones to carry the reader from one state to the next. The process also enables general concepts to be altered, often in unexpected ways. We discuss the application of this model to the process of retroactive reinterpretation, to show how the revision of fundamental knowledge can be understood as a resituation of ‘memory’ among contexts.

In prior work, this approach was developed through sponsorship from the Navy, with the goal of improving ontological interoperability in the intelligence domain. A priority of that program was to preserve contextually specific information and capture its interaction with other contexts (eg. the interaction between different non-logical beliefs). The method thus uses a graphical syntax drawn from ontological knowledge modeling, which is extended using situation theory, to formally account for contextual limits. For the transitional structure needed to step between contexts, narrative provides the mechanisms (Cardier, 2013; Cardier, 2015; Goranson et al., 2015). This work is now being matured in collaboration with the Eastern Virginia Medical School (EVMS), with funding from the National Academies Keck Futures Initiative (NAKFI), as part of its series of advanced interdisciplinary projects.
Retroactive reinterpretation is the focus phenomenon, for the way it fundamentally alters affordances of a system. The process is commonly found in storytelling, and is particularly evident when a tale unfolds in an unexpected yet plausible manner, forcing previous assumptions to change. For example, consider a scene from the television series *Game of Thrones*, in which a usurped princess arrives at a new city and arranges to trade her dragon for a local army. During the scene, she uses the dragon to seize control of the army, keeping both. This outcome adjusts the viewer’s understanding of the situation from ‘trade’ to ‘conquest’, which represents a fundamental shift in the supporting ontological context and the elements within it. Comprehending this shift is critical to anticipating future events, as well as the dragon’s role in determining them (Cardier, 2014).

This early work identified two new important qualities for the computational handling of context. These are: (1) A fact can be situated within multiple contexts simultaneously, and (2) this requires an operator to manage the arrangement of multiple contexts – we use a property termed governance. These characteristics are key elements of retroactive reinterpretation, and our work to model it.

Here, we report on work-in-progress, which applies this approach in the biological domain, where another example of retroactive reinterpretation can be seen. In the body, a ‘fear memory’ incites a combined neurological and cognitive response that can result in post-traumatic stress disorder (PTSD). Treating this condition requires a shift in governance between physical and cognitive systems (Sanford et al., 2013). Like retroactive reinterpretation in narrative, this process resituates a traumatic memory from one system to another, altering its role and effects. In this case, that resituation makes recovery possible. To demonstrate the transportability of this approach, our approach to retroactive reinterpretation is applied to two different domains of intelligent activity: narrative and neurobiology.

Initial modeling of these phenomena using narrative-based principles shows promise, particularly in capturing interaction among multiple, distinct processes at the level of systems. There is currently no satisfactory way to model this kind of interaction between different biological levels and processes (Noble, 2015). We support this at a formal level by supporting switches between frames of reference and implicit or composite agency as first class citizens, in contrast to standard methods. The results to date are accessible through graphical models but not yet coded.

Two dynamics of intelligent systems are thus correlated in this project: first, the resolution of the fear memory that causes medical disorder, and second, the introspective processes of narrative inference. In both cases, a contextual shift alters the fundamental affordances of a system. At the meta-level of modeling, there is also a third connection to intelligence processes: the abstracted mechanisms of narrative cognition. By these means, we develop connections between three different ‘worlds’ of intelligence, indicating where new dimensions of understanding into computational intelligence may lie.

**A Situation-Theoretic Model of Narrative**

Narrative inference is a form of flexible everyday reasoning, which enables the interpretation of partial information under changing circumstances (Herman, 2008; Herman, 2009). For this reason, it was the focus of a project sponsored by the Navy, to design a framework that could handle reasoning about changing contexts and the anticipation of events for which there was no precedent (Cardier, 2013; Cardier, 2015). There is a modest tradition of modeling causal reasoning in narratology (Trabasso & Sperry, 1985; Richardson, 1997; Sturgess, 1992) but those approaches lack the formalism required for the logical audit and computability of contextual nuance required here. We therefore chose situation theory as the foundation, due its capability for rendering contextual dynamics explicitly in a formalizable framework. This framework was then extended using narrative mechanisms.

Our definition of narrative starts with Prince’s description of a story as an event that causes a change of state (Prince, 1973). Cardier’s model built on this premise by expressing ‘state’ as a semantic network, using techniques of ontological knowledge modeling (Cardier, 2013). These states were limited, but could be transformed using notions from conceptual change, which occurs according to a stepwise progression through different but related interpretive states (Thagard, 1992). To account for ‘cause’, Einhorn and Hogarth’s notion of causal fields was used, aligning it with the network of causal dependencies in a semantic network. In line with this, causal agency was defined as an operator capable of “emerging from the background” (Herman, 2002; Mackie, 1980) departing from one network in order to connect it to another (Cardier, 2013).

In this work, an insight from narrative was key: many inferences can be activated simultaneously, causing a partial overlap between their supporting semantic networks (Cardier, 2017). These can be connected even if their structures are fundamentally different. The resulting model of story dynamics thus features semantic networks that are capable of deriving new causal dependencies through interaction with each other (Cardier, 2013; Cardier, 2015; Goranson and Cardier, 2015).

Our outline of this model begins with the notion of ontology, as the computable anchor for these ideas. A general definition of an ontology is that it is a reference framework that records the “objects or entities that are assumed to exist in [a] domain of interest as well as the relationships that hold between them” (Gruber, 1993). Cardier uses techniques of ontological modeling to express multiple aspects of the narrative process: the text itself, the infer-
ences it provokes and the general knowledge from which those inferences draw (Cardier, 2013). These semantic networks have novel additions, to capture the new needed mechanisms of narrative. In the usual style of ontology-based representations, concepts are represented as nodes, and the connections between them are relational links. The method differs from ordinary approaches in that it also groups these structures as situations, which can be nested.

In the below diagram of the original narrative model, notice three main features. First, general knowledge structures are recorded in the top section. As the story text is progressively comprehended, portions of general knowledge are activated and modified by incoming information, as the story progresses. Second, these new arrangements are recorded in the bottom half of the page. Third, connective and transformative structure can be seen stitching these two sections together.

Figure 1: Still image from Cardier’s dynamic model of narrative (Red Riding Hood as a Dictator Would Tell It).

Delving further into the top section of this diagram, notice the uppermost band – the ‘Global Ontology’. When modeling narrative comprehension, this band represents general knowledge. Graphically depicted underneath the Global Ontology are sub-ontologies. They represent the way that, when narrative inference draws on general knowledge, it is limited to a relevant subset, so as not to overwhelm the reasoning process (Sowa, 2011). The above diagram depicts an analysis of the title of the story, “Red Riding Hood as a Dictator Would Tell It”. The sub-ontologies triggered by this sentence are shown to be pulled out of the general ontologies like drawers: ‘Red Riding Hood’ and ‘dictator’. Each of these situations represents a select and limited semantic network. When one is inferred, it becomes dominant over the other, in a manner that will be described in a moment.

The combined structure across the whole field acts as a reference framework, recording the current state of the story-so-far. We refer to this combined framework as a derived ontology. It represents the changing frame of reference used by the reader to understand the incoming text. As the story progresses, this interpretive framework stitches together otherwise incompatible contexts. The resulting structure guides how successive pieces of information are situated and resituated within it (Cardier, 2015).

A key aspect of this structure is the manner in which issues of inheritance are handled. When multiple networks are required for interpretation, a shared frame of reference is derived from them, to produce coherence. This coherence is achieved through the principle of governance. Governance is the imposition of one semantic network on another, altering one or both. The degree depends on a number of factors: compatibility between networks, the state of the story-so-far, and the agencies preserved in each system when they come together. Further study is needed in this area, but a spectrum of adjustment has been identified: a dominant semantic network can entirely replace, partially modify or engage in mutual interaction with another, adjusting heterogeneous terms towards itself (Cardier, 2013).

The notion of governance comes from research into social narratives and cultural theory, in which a person is able to occupy multiple discourses about personal identity simultaneously (Nava, 1992). This drew attention to a similar property of written narrative, where a fact can occupy multiple contexts simultaneously (Cardier, 2013). This activity specifies the interpretive scope at a given instant. When a new event enters the system, it can trigger a rearrangement of the entire structure, as contextual dependencies shift. In retroactive reinterpretation, this process occurs across numerous previously established structures, altering the causal priorities of the system.

The derived ontology is graphically expressed as a causal lattice, as seen in figure 2, on the next page. It can be sliced at any point, to analyze the state at that time. This enables each slice of time to be considered a context. Research under the NAKFI grant is currently modeling the transitions of this lattice, to show how contextual knowledge fundamentally changes as its states evolve. To explain how this research contributes to an understanding
of intelligence in natural and computational systems, we now observe the same processes in neurobiology.

An Example: Fear Memory

Larry Sanford studies fear memory as a modulator of multiple behavioral and biological systems (Sanford et al., 2014). An extreme case is a person who has experienced a trauma and develops PTSD. The resulting ‘fear memory’ can trigger stress, sleep disturbance and immune responses much like those of the initial trauma.

The negative effect of the trauma can be altered by allowing behavioral control during stress. In this protocol, mice receive a mild footshock, but can terminate it by using a simple escape behavior (Sanford et al., 2010). Another treatment is to re-activate the fear memory in a “safe” context. The subject then learns a sense of agency over the process, activating the cognitive processes as dominant.

A distinctive aspect is the way biological and cognitive domains shift in dominance over the fear memory. When the trauma occurs, cognitive processes govern outcomes as much or more than do physical stimuli. Resolution of fear memory involves altering the way the mind (in the cognitive domain) perceives the feared experience. We model this process by correlating narrative switches between inferences with neurobiological switches between the physical systems that govern fear memory. When treating fear memory, the switch between governing processes from biology to cognition can assist healing. This potential alteration of fear memory after trauma suggests a form of retroactive reinterpretation in these two domains – narrative and biology – are discussed further in ‘results’.

The application of a narrative-based method to biology began with a study of olfactory neural regeneration (Goranson & Cardier, 2013). This process also combines two similar domains; the biology is greatly affected by memories associated with scent. (Receptors are tuned to recognize scents from strong experiences.) The PTSD studies are similar in the way they allow us to study several domains in one coherent model. These are:

- Several cognitive processes build a fear memory from experience, then add the new element of control to change a memory’s agency.
- The neural circuitry of the fear memory that incites a biological response, and how that changes when the cognitive shift occurs. This can be handled by mechanisms of contextual interaction, such as a change in governance.
- The process of indirect observation by the scientist, which occurs during experimental design. This is represented in upcoming NAKFI work as both the user’s experience of working with this tool, as well as the principles of design that inform the modeling method itself.

The Method

This work leverages situation theory, which emerged to address contextual reasoning by formal mathematical logic (Barwise & Perry, 1983; Devlin, 1995). For the purpose of ontology design, Goranson and Devlin advanced situation theory in two ways. First, they used Cardier’s extended concept of narrative as a model of how humans cognitively organize facts for recall and communication. The first wide application for situation theoretic system was thus developed by framing narratives as situations, and narrative devices (such as governance) as situational dynamics (Goranson & Cardier, 2013; Goranson et al.; 2015; Devlin, 1995).

Second, these devices are expressed in the second sort of situation theory’s two_SORTED reasoning system. Situation theory formally ties together two frameworks. The first sort is the conventional logic of the domain of interest, known as the ‘right hand side’ (RHS). The second sort was originally a placeholder for real-world situations, known as ‘left hand side’ (LHS). Cardier’s structures replaced this placeholder to capture transitions between fixed, generic knowledge structures. Our left hand side is supported by category theoretic operations, guided by narrative devices.

This formalism shows promise for modeling the ‘soft logics’ humans use in everyday reasoning. The initiating sponsorship from the strategic intelligence community came with a constraint to only abstract within the semantic space. A goal was to avoid the limits of solutions that abstract into probability, vectors and/or geometric spaces.

The graphical and semantic aspects of this work were tested on real written and filmed stories (Cardier, 2014; Cardier, 2015) because these sit between conventional narratology (which is concerned with analysis), and the evolution of meaning needed for the required system. Goranson used that groundwork to model successive facts as structured ‘infons’ with a constrained type system in the expanded situation theory (Goranson et al., 2015). Here, ‘stories’ are expressed as linearized logical statements.

Below is a visual experiment in representing of some of these features in relation to traumatic fear memory (figure 3). In this causal lattice, the colored areas are biological
and cognitive processes – these flow and fold as the depicted system changes. To see a single state, a time-slice can be viewed, indicated by the cuff.

Figure 3: Visualization experiment from the NAKFI project: resolving traumatic fear memory.

**Preliminary Results and Observations**

This research aims to develop an approach that: 1) is purely semantic without recourse to probability or quantitative abstractions; 2) conforms to the way humans structure facts as narratives; 3) allows for implementation as structured models and feasibly executable reasoning systems.

So far, our method has been able to capture the contextual interactions evident in both narrative and the resolution of fear memory. In the course of creating these graphical models, correlations between narrative and cognitive processes have been identified. These indicate the reasoning mechanisms that translate across both cognitive and narrative domains, and which will serve as the basis of the model’s development. Some of these correlations include:

1) A single entity can inhabit two distinct systems/contexts. For example, system sentinels can react similarly to both fear (cognition) and physical stress (biology), so fear memory has agency in both processes. This is similar to interpretation of a fact in narrative. When new information is revealed, a new supporting inference is provoked, re-contextualizing previous facts. Depending on how additional incoming text supports one or the other, interpretation shifts back and forth (Cardier, 2013).

2) If a shift between contexts is substantial enough, it can recast all previous structure until the entire system responds differently to new information. This change includes casual affordance and thus alters potential outcomes. In the fear extinction case, the immune system situates a previously understood fear event and ceases to attack. In narrative, a character who initially seemed to be a dupe can be suddenly revealed as a mastermind, for example, in *Game of Thrones* (Cardier, 2014).

3) When many systems interact, one can be dominant. In the example, the cognitive system dominates when fear learning occurs, and becomes dominant again after the fear memory has been modified. We will explore whether interactions between systems fall on a spectrum, similar to the replace, modify or mutual relations observed among narrative inferences (Cardier, 2013).

Figure 3, left, is an illustration of how facts will map onto a larger concept lattice of interacting systems. Here, the flow on the top is cognitive space, the center is the cognitive hardware and activity in different parts of the brain. The bottom represents the unfolding actions of the immune systems. These interlink at key points.

Notably, this figure also demonstrates some of the display challenges encountered so far. Our model can record the above characteristics but their structures are difficult to read once structure accumulates. This difficulty is also due to the simultaneous depiction of macro and micro scales.

We address this problem at a fundamental level, by adding another dimension to our notion of intelligent reasoning: emergent design. The premise is that emergent structure eventually produces self-referential principles that manage its morphology. This project will draw from Cassas’s research into the relationship between principles of design, energy conservation and optimal efficiency to inform transformations of the causal lattice.

**Implementation Issues**

An early prototype of the two-sorted reasoning system with simple content was demonstrated within the intelligence community by Goranson. This experience and subsequent work indicates that using functional code, higher categories and open source projects like Apache Heron, the implementation of the left hand side will be economical and without showstoppers.

On the other hand, managing knowledge on the right hand side to cooperate with the method could be expensive and, in some applications, impractical. The primary problem is that we require high ontological hygiene. NIH data sources are the most ordered in this regard, and the NIH-sponsored basic formal ontology (BFO) the best considered standard upper ontology. BFO underlies cognitive, psychological phenomes and neurobiology (Bilder et al., 2009). Some planning has begun on extending BFO.

We have not yet developed a suitable formal visualization for implicit influences in biology. This will be addressed in planned examples that include the influence of overlapping, highly reconfigurable communities of the gut microbiome, continuing work with EVMS.
Future Work

One goal is to address problems associated with ontological interoperability in neurobiological modeling. Current efforts to standardize or integrate ontologies in this domain have been disappointing (Walls et al., 2014). To address this, Goranson framed Sanford’s work to be accessible to biomedical ontologies, structuring information according to our mechanisms. One concession to biology is the development of a new type system (Goranson et al., 2015) that subsumes the original cognitive domain, includes biological dynamics, and conforms to biomedical ontologies and common practice (Goranson & Cardier, 2013).

The work for NAKFI will include a study of how principles of design inform transformations of the causal lattice. This will address readability and navigation issues in a non-superficial manner, with choices about representational modeling rooted in theories of forgetting (neurobiology) plus emergent pattern, decay and optimal form (design).

Conclusions

This early work indicates that we may usefully model biological dynamics, including neurocognitive processes, using mechanisms drawn from narrative. Our method captures switches in governance among different, seemingly distinct processes and the accompanying alteration of causal dependencies. This early work indicates that we may usefully capture properties of intelligence across multiple disciplines using this model. Further work is required to address readability and navigation issues with the visualization. Future research will also focus on ontological primitives for stateful situations.

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References


