Impulse: A Formal Characterization of Story*

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Abstract

We present a novel representation of narratives at the story level called Impulse. It combines a temporal representation of a story's actions and events with a representation of the mental models of the story's characters into a cohesive, logic-based language. We show the expressiveness of this approach by encoding a story fragment, and compare it to other formal story representations in terms of representational dimensions. We also acknowledge the computational complexity of our approach and argue that a restricted subset still provides a high degree of expressive power.

1998 ACM Subject Classification F.4.1 Mathematical Logic

Keywords and phrases Narrative, logic, representation, mental models, time

Digital Object Identifier 10.4230/OASIcs.CMN.2015.45

1 Introduction

Narrative is used across cultures to convey both fictional and non-fictional stories. This ubiquity has led to narrative research in many fields, from narrative theory to linguistics to cognitive psychology to AI. Within AI, research ranges from understanding and reasoning about existing narratives to generating new ones. In this field, the division narratologists make between *story* and *discourse* is often used [3]. The story consists of the events that happen in the story world while the discourse describes how these events are told. For example, a story may consist of a murder, an investigation and an arrest, in that order, but a movie rendition may start with the investigation and end with a flashback to the murder to "reveal" the murderer, i.e. the order the events are shown differs from the order in which they actually happened.

We propose a representation for the story level of a narrative called Impulse. In addition to the representation of core story elements such as events and actors, it also provides means to encode information that is not essential to the story but may be relevant for reasoning about possible discourses. Furthermore, Impulse allows complex reasoning about the story itself. We will show how this reasoning can be used to derive explanations for characters' actions or beliefs. We claim that Impulse provides a strong basis for building systems to computationally reason over stories, for story understanding, analysis, as well as for discourse generation.

* This material is based upon work supported in whole or in part with funding from the Laboratory for Analytic Sciences (LAS). Any opinions, findings, conclusions, or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the LAS and/or any agency or entity of the United States Government.

6th Workshop on Computational Models of Narrative (CMN'15).
Editors: Mark A. Finlayson, Ben Miller, Antonio Lieto, and Remi Ronfard; pp. 45–53
OpenAccess Series in Informatics
OASICS Schloss Dagstuhl – Leibniz-Zentrum für Informatik, Dagstuhl Publishing, Germany

2 Related Work

Due to the wide variety of research interests of scholars building computational models of story, there is also a variety of representations, each highlighting different aspects of a story. Elson and McKeown [5] describe a system for encoding stories in graphs, designed to allow structural comparison between different narratives. A tool allows for easy encoding, annotation and comparison of stories, but it lacks rich formal inference rules.

Some story generation systems also produce stories in a representation that is suitable for further processing. For example, partial-order causal link planning with intentions (IPOCL) has been described as a generative approach for stories by Riedl and Young [13], as an improvement over their previous work with POCL plans [12]. An IPOCL plan consists of steps, that are linked to other steps with causal and temporal links, and frames of commitment that represent character intentions. The model of time in the plan is necessarily simple, to keep the planning process computationally feasible. Furthermore, there is no representation for character beliefs. Very closely related to planning is Martens *et al.*'s [9] use of Linear Logic to generate stories, but their representation does not include time or actors' mental models either.

Ontologies are also often used to represent stories, for example in the Drammar model [8]. Drammar provides an operationalization of a Belief, Desire, Intention (BDI) model represented as an ontology. Swartjes and Theune [14] have elaborated on an earlier version of this ontology by incorporating Trabasso *et al.*'s General Transition Network [16]. However, these approaches only consider relative ordering of steps. Swartjes and Theune also reiterate the point made by Tuffield *et al.* [17] that formal characterization of story generation systems' outputs is still lacking. In particular, when the story is to be presented to an audience by a discourse generator, representing exact timing information is crucial. The discourse generator Darshak, for example, uses a representation of time, based on the planning algorithm DPOCLT, for precisely that reason [7]. When using external data sources, such as video games, precise timing information is available, but if this knowledge can not be represented, it would be lost and could not be reasoned about.

Allen and Ferguson's representation of actions and events in interval temporal logic (ITL) allows complex reasoning over time [2], and remedies shortcomings of the situation calculus [10], like the frame problem. It is based on predicate logic, uses intervals as its representation of time, and includes actions as first-class objects. The representation already allows rich reasoning about the story content and deduction of new facts, but does not contain any model of the actors' mental models. On the other hand, Cohen and Levesque's [4] BDI model, which is also based on predicate logic, allow the representation of, and reasoning about, actors' mental models that would allow inferences about characters' motivations, but does not include a representation of time. We present a novel representation of narratives at the story level, called Impulse, that combines ITL with a BDI model to improve upon the limitations of these representations.

3 Representation

Impulse is based on ITL, a representation based on predicate logic, and augments it with a BDI model of actors. We will first describe the temporal representation we use and how it can be reasoned about. Then we will discuss how time can be added to predicate logic, and how to represent actions and objects in a story, closely following ITL. We then discuss the integration of BDI models with this temporal representation.

Table 1 Allen's interval relations and their representation in Impulse.

Name	Allen	Definition	Notation
Equal	$t_1 = t_2$	$\text{start}(t_1) = \text{start}(t_2) \land \text{end}(t_1) = \text{end}(t_2)$	$t_1 = t_2$
Before	$t_1 < t_2$	$\text{end}(t_1) < \text{start}(t_2)$	$t_1 \prec t_2$
Meets	$t_1 \text{ m } t_2$	$\text{end}(t_1) = \text{start}(t_2)$	$t_1 : t_2$
During	$t_1 \text{ d } t_2$	$\text{start}(t_1) > \text{start}(t_2) \land \text{end}(t_1) < \text{end}(t_2)$	$t_1 \sqsubset t_2$
Starts	$t_1 \text{ s } t_2$	$\text{start}(t_1) = \text{start}(t_2) \land \text{end}(t_1) < \text{end}(t_2)$	$t_1 \triangleleft t_2$
Finishes	$t_1 \text{ f } t_2$	$\text{start}(t_1) > \text{start}(t_2) \land \text{end}(t_1) = \text{end}(t_2)$	$t_1 \blacktriangleright t_2$
Overlaps	$t_1 \text{ o } t_2$	$\text{start}(t_1) < \text{start}(t_2) < \text{end}(t_1) < \text{end}(t_2)$	$t_1 \rightsquigarrow t_2$

3.1 Representation of time

Impulse uses intervals as its unit of time. Conceptually, an interval t is a non-empty "stretch" of time, with a start and an end, denoted by $\text{start}(t)$ and $\text{end}(t)$, respectively. We will denote the set of all possible intervals with T, called the *time basis*. Two intervals can be in one of 13 different relations to one another, called Allen's interval relations [1]. Table 1 gives an overview of 7 of them with the notation used in Impulse, where the missing 6 are simply the inverses of all but the equality relation.

▶ **Definition 1.** Multiple basic interval relations can be combined into a set $\{R_1, \dots, R_n\}$, where each of the R_i is one of Allen's 13 interval relations. Then $t_1\{R_1, \dots, R_n\}t_2 \Leftrightarrow t_1 R_1 t_2 \lor \dots \lor t_1 R_n t_2$.

One important complex relation is the subinterval relation:

▶ **Definition 2.** An interval t_1 is a *subinterval* of an interval t_2, written $t_1 \sqsubseteq t_2$, iff the two intervals are the same, or t_1 is during, starts or finishes t_2, i.e. $t_1 \sqsubseteq t_2 \Leftrightarrow t_1\{\sqsubset, =, \triangleleft, \blacktriangleright\}t_2$.

3.2 Temporal and atemporal predicates and functions

To make the step from predicate logic to one based on time, predicates and functions can now have an additional "time" parameter over which they hold. We call predicates and functions with this parameter *temporal* and those without *atemporal*. For example $at(John, Library, t)$ means "John was at the Library for the interval t", and at is a temporal predicate. We use the same concepts of strong and weak negation as Allen and Ferguson:

▶ **Definition 3.** The *strong* negation of a temporal predicate P over an interval t, written $\neg P(p_1, \dots, p_n, t)$ states that the predicate is false during any subinterval of t, i.e.

$$\neg P(p_1, \dots, p_n, t) \Leftrightarrow \neg \exists t_1 \in T \; t_1 \sqsubseteq t \land P(p_1, \dots, p_n, t_1) \,.$$

▶ **Definition 4.** The *weak* negation of a temporal predicate P over an interval t, written $\sim P(p_1, \dots, p_n, t)$ states that the predicate is false during some subinterval of t, i.e.

$$\sim P(p_1, \dots, p_n, t) \Leftrightarrow \neg \forall t_1 \in T \; t_1 \sqsubseteq t \rightarrow P(p_1, \dots, p_n, t_1) \,.$$

Furthermore, we require all predicates used in Impulse formulas to be homogeneous.

▶ **Definition 5.** A predicate is called *homogeneous* iff it being true over some interval t implies that it is also true over every subinterval of t, i.e.

$$\forall t_1 \in T \; P(p_1, \dots, p_n, t) \land t_1 \sqsubseteq t \rightarrow P(p_1, \dots, p_n, t_1) \,.$$

Temporal functions present another challenge, as they may change value over time, leading to situations where their value may be undefined, i.e. functions are partial with respect to time. For example, if $f(t_1) = a$ and $f(t_2) = b$, the value of $f(t_3)$, with $t_1 \sqsubseteq t_3 \wedge t_2 \sqsubseteq t_3$, is undefined. Using an undefined value in any way will propagate that value, and any predicate on an undefined parameter does not hold.

3.3 Representation of objects and actions

Objects in Impulse are objects in the predicate logic sense, representing concrete and abstract entities in the story world and being uniquely identified by name. All objects in the story are collected in a set O, of which arbitrary subsets can be defined to be used by formulas. Two of these subsets, $A \subseteq O$ and $L \subseteq O$, represent the actors and locations in the story respectively, and have to be defined for all stories. These subsets provide a "type system" for the objects, allowing sentences to refer to objects of specific types. For example, a sentence could say that all locations are cold, without saying anything about other objects.

Similar to objects, actions are elements of a set called *Actions*, with a subset defined for each different action type. For example, there could be a *move*-action set, which is a subset of *Actions*, containing all possible *move*-actions. Normally, we will not be concerned with all possible actions, but only with those that actually happened or could have happened in a particular story. What determines the uniqueness of each action are its properties:

▶ **Definition 6.** A *property* p of an action type $Y \subseteq \mathit{Actions}$ is an atemporal function $p : Y \mapsto O$.

For example, an action of type *openDoor* may have a property door : $\mathit{openDoor} \mapsto \mathit{Doors}$ that refers to the door being opened by a specific action of the action type *openDoor*. Additionally, properties of temporal values are also supported:

▶ **Definition 7.** A *time interval property* q of an action type $Y \subseteq \mathit{Actions}$ is a function $q : Y \mapsto T$.

To distinguish between actions that actually happens in the story and those that are only part of the reasoning process of some character, a predicate occurs is introduced.

▶ **Definition 8.** The atemporal predicate $\text{occurs}(e)$ holds if and only if e is an action that actually happens in the story.

An action will typically have some predicates associated with it that have to hold for the action to be possible, and other predicates that describe the effect of the execution of that action. Like ITL, Impulse uses Skolem functions called pre$n$ and eff$n$ on actions to describe the duration of their preconditions and effects. Suppose we have an action "open the door", then its effect can be encoded as $\forall s \in \mathit{openDoor}\ \exists t_1, t_2\ \text{occurs}(s) \wedge \text{closed}(\text{door}(s), t_1) \rightarrow \text{open}(\text{door}(s), t_2)$. However, this leaves us with the existentially quantified variables t_1 and t_2 that depend on the story, i.e. when the *openDoor* action happens, and when the door was previously closed. Allen and Ferguson argue that the sentence $\forall s \in \mathit{openDoor}\ \text{occurs}(s) \wedge \text{closed}(\text{door}(s), \text{pre1}(s)) \rightarrow \text{open}(\text{door}(s), \text{eff1}(s))$ is equivalent to the preceding encoding, but now the intervals depend on the action instantiation directly, and we can now also refer to them in formulas.

3.4 Actors' mental models

Impulse uses a simplified representation of actors' mental models, in the form of a BDI representation. This has previously been used for narrative representation [11]. It allows us to represent character beliefs, which are important to reason about disparity between their views of the world, and - when used with a discourse realizer - with the audiences view of the world as well as their desires and intentions which are important to reason about how to deduce and convey character motivations. While this model does not capture every aspect of character's mental models (e.g., emotional state), we argue that a limitation of the representation is essential to allow inferences to be made in a reasonable manner, and that a BDI model provides sufficient details to reason about a story for discourse generation. It is also possible to extend this mental model representation for specific applications, or to represent emotional states as predicates in the existing Impulse formalism.

Because of our representation of time, the modal operators for belief, desire and intention had to be modified to include a temporal parameter as well:

▶ **Definition 9.** $B_a(t)\Phi, D_a(t)\Phi$ and $I_a(t)\Phi$, with $a \in A$ an actor, t a time interval over S and Φ an arbitrary Impulse formula represents that actor a *believes, desires* or *intents* the formula Φ, respectively.

Note that the temporal parameter actually belongs to the modal operator. Φ will contain its own temporal information. This allows us to represent complex relations like "From 8AM to 10AM John believed that dinner would be served from 7PM to 8PM, but then someone told him that it was actually served from 6PM to 7PM, so he revised his belief".

The only property Impulse enforces on beliefs, desires and intentions is homogeneity:

▶ **Definition 10.** Beliefs, Desires and Intentions are homogeneous, with respect to time, i.e. $\forall t\, \forall t_1\ (B_a/D_a/I_a(t)\Phi \wedge t_1 \sqsubseteq t) \Rightarrow\ B_a/D_a/I_a(t_1)\Phi$.

Other properties often encountered in BDI models can be defined as needed. For example, one may want to define that beliefs are always consistent:

▶ **Definition 11.** $\forall t : B_a(t)\Phi \Rightarrow \neg B_a(t)\neg\Phi$, for any Impulse formula Φ.

3.5 Story representation

A complete story consists of:

- a time basis T, which is a set of intervals,
- an object hierarchy, with O the set of all objects and a definition of subsets thereof,
- an action hierarchy, with *Actions* the set of all actions and a definition of subsets thereof,
- a set of action properties P, as functions mapping from actions to objects or intervals,
- a set of actions Σ that occur in the story. This means $s \in \Sigma \Leftrightarrow \text{occurs}(s)$,
- a set of Impulse sentences Ψ

With this representation, a deduction system can reason about the story by applying logical operations on the sentences in Ψ and deriving new facts. Alternatively, an explanation system could remove steps from Σ or add new ones and then reason about "what would have happened". A discourse generation system, on the other hand, can reason about which information has to be presented to the audience, and which one can be deduced. Depending on what should be conveyed, it may also decide to show or not show the duration of actions.

4 Evaluation

4.1 Example

The example presented here is a shortened version of a scene from the movie "The Lord of the Rings: The Fellowship of the Ring", based on the book of the same name [15]. In the movie, Isildur, the king of men, comes into possession of a magical ring. One of his allies, the elf Elrond, knowing that the Ring is "evil", advises him to destroy it, but the Ring has too much influence over its bearer. In the movie, this leads Elrond to conclude that men are weak. For space reasons, we omit many of the movie's actions and only present the most important ones.

As a time basis, we use intervals over the natural numbers, so $T \subseteq \mathbb{N} \times \mathbb{N}$, and denote "the interval starting at (and including) a and ending at (and not including) b" with ${}_at_b$. The objects in the story include *Elrond*, *Isildur* and *Ring*, so $O = \{Elrond, Isildur, Ring, Aragorn, \acute{E}owyn, \ldots\}$, the set of actors is $A = \{Elrond, Isildur, Ring, Aragorn, \acute{E}owyn\} \subseteq O$ and the set of locations $L = \{\} \subseteq O$. We also define a set $Humanoid = \{Elrond, Isildur, Aragorn, \acute{E}owyn\}$ used to prevent the Ring from actively doing anything, and a set $men = \{Isildur, Aragorn, \acute{E}owyn, \ldots\}$ containing all the human actors[1]. The Ring plays a special role in the story, so the function bearer(t) is used to keep track of who is the Ring-bearer at any given time. We have three action types:

- *get* represents an actor getting the Ring. It has the associated property actor : $get \mapsto Humanoid$, and a single effect duration eff1 : $get \mapsto T$
- *tellToDestroy* represents an actor telling another one to destroy the Ring. It has the properties actor : $tellToDestroy \mapsto Humanoid$, recipient : $tellToDestroy \mapsto A$, one precondition duration pre1 : $tellToDestroy \mapsto T$ and two effect durations: eff1, eff2 : $tellToDestroy \mapsto T$
- *succumb* represents an actor succumbing to the will of the ring, it has one property actor : $succumb \mapsto Humanoid$ and two effect durations eff1, eff2 : $succumb \mapsto T$

Note how *tellToDestroy* can only be performed by a *Humanoid*, but the recipient may be any actor. So, in theory, an actor could tell the Ring to destroy itself. These actions don't actually "do" anything, though, so we need to define what happens when they occur in a story:

1. $\forall s \in get \text{ occurs}(s) \to \text{bearer}(\text{eff1}(s)) = \text{actor}(s)$
2. $\forall s \in tellToDestroy \text{ occurs}(s) \wedge \text{allies}(\text{actor}(s), \text{recipient}(s), \text{pre1}(s)) \to$
   $D_{\text{recipient}(s)}(\text{eff1}(s))\, \text{destroyed}(Ring, \text{eff2}(s))$
3. $\forall s \in succumb \text{ occurs}(s) \wedge \text{bearer}(\text{pre1}(s)) = \text{actor}(s) \to$
   $I_{\text{actor}(s)}(\text{eff1}(s)) \neg\, \text{destroyed}(Ring, \text{eff2}(s))$

The other Impulse sentences representing the story are:

4. $\text{allies}(Isildur, Elrond, {}_1t_{10})$
5. $\forall t \in T\ \forall a, b \in A\ \text{allies}(a, b, t) \to \text{allies}(b, a, t)$
6. $\forall t\ D_{Ring}(t) \neg\, \text{destroyed}(Ring, t)$
7. $\forall t\ D_{Elrond}(t)\, \text{destroyed}(Ring, t)$
8. $\forall t \in T\ B_{Elrond}(t)\, \text{weak}(Isildur, t) \to \forall m \in men\ B_{Elrond}(t)\, \text{weak}(m, t)$
9. $\forall t \in T\ D_{Ring}(t)\Phi \to D_{\text{bearer}(t)}(t)\Phi$
10. $\forall t \in T\ t_1 \in T, \forall a \in A,\ D_a(t)\Phi \wedge D_a(t)\neg\Phi \wedge D_{Elrond}(t)\Phi \wedge I_a(t)\neg\Phi \wedge t : t_1 \to$
    $B_{Elrond}(t_1)\, \text{weak}(a, t_1)$

All these sentences form the set Ψ. Additionally, we have to state which actions actually occur in the story, and the values of their properties, i.e. the contents of Σ:

- $s_1 \in get$ with $\text{actor}(s_1) = Isildur$, $\text{time}(s_1) = {}_1t_2$, $\text{eff1}(s_1) = {}_2t_5$
- $s_2 \in tellToDestroy$ with $\text{actor}(s_2) = Elrond$, $\text{time}(s_2) = {}_2t_3$, $\text{recipient}(s_2) = Isildur$, $\text{pre1}(s_2) = {}_1t_2$, $\text{eff1}(s_2) = {}_3t_5$
- $s_3 \in succumb$ with $\text{actor}(s_3) = Isildur$, $\text{time}(s_3) = {}_3t_4$, $\text{pre1}(s_3) = {}_2t_3$, $\text{eff1}(s_3) = {}_4t_5$, $\text{eff2}(s_3) = {}_4t_{10}$

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[1] As in the movie, we use "men" to refer to "the race of men", i.e. humans, rather than "males".

Table 2 Comparison of the expressiveness of Impulse and other story representations.

Story aspect	IPOCL	ITL	BDI	SIG	Drammar	Impulse
Temporal representation	Limited[a]	Rich	None	Limited[a]	None	Rich
Beliefs	None	None	Rich	Rich	Rich	Rich
Desires	None	None	Rich	Rich	Rich	Rich
Intentions	Limited [b]	None	Rich	Limited[c]	Rich	Rich
Alternate timelines	None	Rich[d]	None	Rich	None	Rich[d]
Formal semantics	Rich	Rich	Rich	Limited[e]	Rich	Rich

[a] Relative order and instantaneous steps; DPOCLT has durations but only simple interval relations
[b] Intentions are used to justify why actions are taken, but no further reasoning is done on them
[c] Story Intention Graphs only have "goals", and no strong distinction between "desires" and "intentions"
[d] Alternate/imagined timelines can be represented by sequences of actions that did not occur
[e] Story Intention Graphs allow comparison of stories, but there are no formal inference rules

Together, the time interval, object hierarchy, action hierarchy, action properties, sentences and occurring actions form the "story". We can now derive additional information about it:

11. $\text{allies}(\mathit{Elrond}, \mathit{Isildur}, {}_1t_2)$ (from 4 and 5, and homogeneity of predicates)
12. $\text{bearer}({}_2t_5) = \mathit{Isildur}$ (from 1 and $s_1 \in \mathit{get}$)
13. $D_{\mathit{Isildur}}({}_3t_5)\,\text{destroyed}(\mathit{Ring}, {}_3t_5)$ (from 2, 11 and $s_2 \in \mathit{tellToDestroy}$)
14. $D_{\mathit{Isildur}}({}_3t_5)\neg\,\text{destroyed}(\mathit{Ring}, {}_3t_5)$ (from 6, 9 and 12)
15. $I_{\mathit{Isildur}}({}_4t_5)\neg\,\text{destroyed}(\mathit{Ring}, {}_4t_{10})$ (from 3, 12 and $s_3 \in \mathit{succumb}$)
16. $B_{\mathit{Elrond}}({}_4t_{10})\,\text{weak}(\mathit{Isildur}, {}_4t_{10})$ (from 7, 10, 13, 14, 15 and homogeneity of desire)
17. $\forall m \in \mathit{men}\ B_{\mathit{Elrond}}({}_4t_{10})\,\text{weak}(m, {}_4t_{10})$ (from 8 and 15)

We thus conclude that Elrond believes men to be weak. In the movie, this is conveyed as a flashback. With Impulse, a discourse generator could reason about the story to generate such a scene, or a story authoring tool could be used to explore what changes would prevent this belief from forming, e.g. an alternative story in which Elrond believes in the strength of men.

4.2 Expressive power

As the example above demonstrates, Impulse allows for rich reasoning about facts in the story and the mental models of the actors. Table 2 shows a comparison between Impulse and other story representations discussed in section 2 in terms of which aspects of the story they can represent. As can be seen in this table, other representations are more limited in their representation of time or actors' mental models when compared to Impulse.

4.3 Usage

The expressive power of Impulse comes with a price: computational complexity and even decidability. Since Impulse is an extension of predicate logic, which is already undecidable in the general case [18] and computationally expensive in many others, using it as-is is not feasible. However, just like Horn clauses [6] are a subset of predicate logic that allows a more efficient reasoning process while still providing expressiveness, subsets of Impulse can be identified for similar uses. We propose to limit all sentences to two forms:

- *Facts* are single predicates without any connectives, but with optional quantifiers, e.g. $\forall t\ D_{\mathit{Ring}}(t)\neg\,\text{destroyed}(\mathit{Ring}, t)$

- *Rules*[2] consist of a single implication, where both the antecedent and the consequent consisted of "and"-connected facts, also with quantifiers, e.g.
  $\forall t \in T\ \forall a, b \in A\ \text{allies}(a, b, t) \rightarrow \text{allies}(b, a, t)$

Limiting the sentences to these two forms allows us to use a slightly modified variant of forward chaining, that accounts for the temporal aspect of the logic, as a more efficient method for deriving new information. As the Lord of the Rings example demonstrates, these two forms are sufficient to represent and reason about a complex narrative.

Since Impulse is designed for story representation rather than for generation, data must be acquired and encoded in Impulse somehow. There are several ways this can happen. One approach is to use a story encoded in another representation, for example as an IPOCL plan, and translate it to Impulse. Then this story could be annotated manually or automatically to make use of Impulse's richer representation of time and actors' mental models, for example by using a scheduler, or doing intention recognition. Another rich data source for content describable in Impulse are log files of video games. They often contain very detailed information about the states of the world and which actions are performed by actors over time, as well as having detailed and formal rules for the effects of their actions. A discourse generator could use this information to provide e.g. a summary of the game in an engaging way.

5 Conclusion

We presented Impulse, an expressive logical representation for stories that incorporates representations of time and actors' mental models of the world. It draws from Allen and Ferguson's work on Interval Temporal Logic and combines it with a BDI model, which is modified to also account for time. We demonstrated how this approach can be used to model a simple story fragment and reason about its actors' mental models. We then compared the expressive power of our representation to that of other approaches. We also acknowledged the computational complexity of the reasoning process on our representation, and how it can be limited for some particular use cases. We argue that one such restriction yields an efficient, yet expressive deduction scheme. An actual implementation of this deduction system is currently being worked on.

While we claim that this representation could be used in a discourse generator, a tighter integration and a representation of the discourse itself still remains as future work.

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