

Intelligent Systems: Reasoning and Recognition

James L. Crowley

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Lesson 18

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Bayesian Narrative Reasoning

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Bibliography:

- 1) P. N Johnson-Laird, Mental models, MIT Press Cambridge, MA, USA, 1989.
- 2) P. Abell, Narratives, Bayesian narratives and narrative actions. *Sociologica*, 1(3), 2007

Narratives



Calvin and Hobbes: Dad explains science

Why is it raining? "A cold front is approaching from the north-west drawing warm moist air from the Mediterranean and causing it to rise into cold air from the north."

Why are you late for class? "I missed the bus and had to walk."

These are examples of Narratives.

A Narrative is a temporal sequence of Situations.

Humans use Narratives to understand phenomena.

Narratives enable humans to provide rich descriptions for situations that are not directly observable, including situations that occurred in the past, and hypothetical or abstract situations.

Narratives enable humans to make predictions for situation that may occur in the future.

In this lecture we will

- 1) Revisit Situation Modeling to provide a formal foundation for narrative reasoning.
- 2) Show how temporal sequences of situations can be used to provide rich descriptions of unobserved phenomena, and predict the likelihood of future phenomena.
- 3) Show how to collect evidence for and against the likelihood of competing narratives using Bayesian reasoning

Situation Models (revisited)

Situations models are used in cognitive science to describe the mental models that people use to understand and reason. Situation models can be used to

- (1) Providing meaning and explanations for phenomena
- (2) Describe phenomena that cannot be observed
- (3) Predict phenomena that have not yet occurred.

A situation model is a directed graph where the nodes represent situations and the arcs represent events. A situation model is a form of state space.

Situations

A Situation is a set of relations over entities (a state).

We can define a situation as a frame for interpreting observed phenomena (entities).

```
(Defclass SITUATION (is-a FRAME)
  (slot SName) ;;; situations have a unique name
  (multislot Entities) ;;; concrete instances of concepts.
  (multislot Relations) ;;; Relations between entities;;
)
```

A situation model can be defined as a pair: $\{\underline{X}\}\{\underline{R}\}$

- 1) A set of Entities $\{\underline{X}\}$: Instances of concepts that represent phenomena.
- 3) A set of Relations $\{\underline{R}\}$: Predicates over subsets of Entities.

Entities are instances of concepts.

Narrative Reasoning

Concepts

Concepts are abstract representations for phenomena. Concepts arise as abstractions or generalizations from experience or from the transformations of existing concepts. Concepts can be learned from experience or by communication. Concepts can represent words, actions, perceived phenomena, experiences, feelings, etc.

Concepts have a name, a definition, and a meaning.

```
(defclass CONCEPT (is-a USER) ;; concepts are abstract classes.
  (slot CName) ;; Concepts have a unique name.
  (multislot Meaning) ;;; pointers to experiences
  ;;; (episodic memory)
)
```

The definition for concept is a procedure that can determine if an entity (observed or recalled phenomena) is an instance of the concept. In CLIPS, a definition can be defined as Boolean message-handler.

```
(defmessage-handler CONCEPT definition (?Entity)
  ..recognition test.... )
```

The definition for a concept can be Intensional or Extensional. An Intensional definition specifies a test (or set of tests) that determine if an entity is an instance of the concept. An Extensional definition provides a list of entities that can be identified as belonging to the concept.

Entities

Entities are recognized as concrete instances of concepts with specific properties.

```
(defclass PERSON (is-as Concept) (role concrete)
  (slot first-name)
  (slot family-name)
)
```

```
(bind (?entity1 (make-instance John of PERSON
  (first-name John) (family-name Jones)))
```

Entities can be represented as concepts either by a recognition procedure, or by a reasoning process that composes a complex entity from an assembly of more primitive entities (chunking).

Narrative Reasoning

Relations

Relations organize entities for reasoning. Examples include Ordinal Relations, Spatial Relations, Temporal Relations, Organizational Relations, and Family Relations.

Relations are represented with predicates (truth functions). The truth-value of a relation depends on the properties of entities that form its arguments.

We will use explicit representations of relations, so that relations can change without changing the underlying entities.

```
(defclass RELATION (is-a USER) (role concrete)
  (slot Rname) ;; unique name for the relation
  (slot Arity) ;; number of arguments
  (multislot Arguments)
)
(defclass Father (is-a RELATION) (role concrete)
  (slot Arity (default 2)) ;; number of entities
  (slot Child)
  (slot Father)
)
(make-instance F1 of Father (?child ?father))
```

Events

Events are operators that change situations by changing the set of relations. These could be similar to "actions" in planning. However, actions connote the agency of an actor or agent. Not all changes in situation are the result of actions by an agent.

$$P(S_1) - E_{12} \rightarrow P(S_2) - E_{23} \rightarrow P(S_3) - E_{34} \rightarrow P(S_4)$$

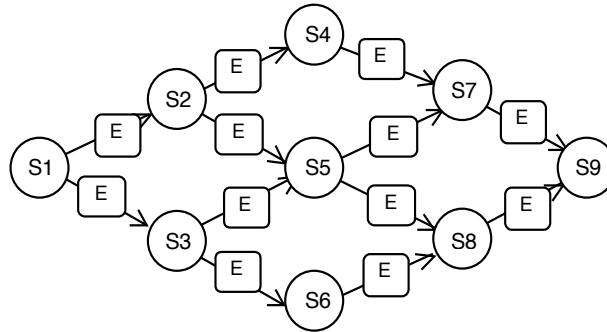
```
(defclass Event (IS-A USER)
  (slot EName)
  (slot PreCondition) ;;; Situation before the event
  (slot PostCondition) ;;; Situation after the event
)
```

Narrative Reasoning

Situation Models

A Situation Model is a directed graph of situations.

Nodes are situations. Arcs are events.



The set of Concepts, Relations, and Events are said to compose the Ontology for the Situation. This is sometimes called the "context".

```
(Defclass SITUATION-MODEL (is-a Frame)
  (slot SName)   ;;; unique name
  (multislot Concepts) ;;; Schema for organizing phenomena
  (multislot Relations) ;;; Relations between entities
  (multislot Situations) ;;; A set of situations
  (multislot Events) ;;; Operators that change situations
)
```

A situation model can be defined as a set of 4 sets: $\{X\}\{R\}\{E\}\{S\}$

- 1) A set of Entities $\{X\}$: Concrete instances of concepts.
- 3) A set of Relations $\{R\}$: Predicates over subsets of the Entities in $\{X\}$
- 4) A set of Events $\{E\}$: Operators that can change Situations by changing Relations.
- 5) A set of Situations $\{S\}$: A set of situations that share entities and relations

Situation models are typically limited to a finite set of entities in order to avoid an exponential explosion in the set of possible relations. Fortunately, for most problem domains, we can generally limit the number of entities, the number of concepts and the number of relations to small sets this makes the situation model tractable.

Narrative Reasoning

Observability

In the real world many situations are not directly observable! For example, we can not observe situations that occurred in the past, hypothetical situations, or situations that will occur in the future.

In this case, a situation model is said to be "Partially Observable". In addition, situation models can be defined for concepts that are not directly observable!

Examples include radio waves, phenomena that are too slow or too fast for human perception (global warming, ultrasound, infrared light), or too large or too small for human perception (atoms and molecules, the Universe).

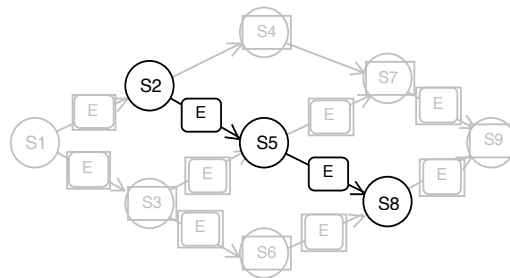
Humans use Narratives to reason and communicate about unobservable phenomena and partially observable phenomena.

Narratives

A Narrative is a temporally ordered sequence of Situations.

Typically situations in a narrative have a duration and are ordered by time relations.

A Narrative represents a path through a situation graph.



```
(defclass Narrative (is-a FRAME)
  (slot Ontology) ;;; defines concepts, relations and events
  (slot Belief) ;;; estimation of the credibility.
  (slot S1) ;;; the initial situation
  (slot E12) ;;; The event that causes transition from S1 to S2
  (slot S2) ;;; the initial situation
  (slot E23) ;;; The event that causes transition from S1 to S2
  .....
  (slot Sn) ;;; the final situation
)
```

Narratives are an essential part of human reasoning.

For example, a personal narrative is an essential part of our self-identity.

Narratives are commonly used in public discourse to explain and predict social phenomena. Scientific theories are a form of narrative for explanation and prediction of phenomena.

A Narrative provides an explanation for a situation by describing previous (non-observable) situations. A narrative can provides predictions of situations that will occur in the sequence after the current situation. Narratives provide explanations by describing how events can change the relations between entities.

A Situation model can be used to "infer" the occurrence of non-observable entities, relations and events.

Narrative Reasoning

Entailment

An entailment is a predicate is implied by a statement.

A situation "entails" the predicates that define it. If the situation occurs, then the relations of that situation are assumed to be true.

$$S \vdash r_1(X_1) \wedge r_2(X_2) \wedge \dots \wedge r_n(X_n)$$

Where S is a situation.

$r_1(X_1), r_2(X_2), r_n(X_n)$ are relations in the situation,

X_1, X_2, X_n : are sets of entities in the situation.

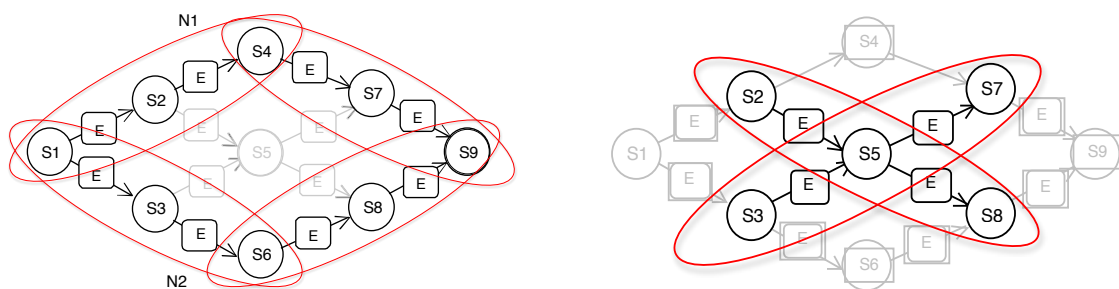
If a relation is not directly observable it is entailed by a situation.

If an entity X is not directly observable, then the relation $\text{Exists}(X)$ is entailed.

$$S \vdash \exists(X_1)$$

$\text{Exists}(X)$ can be included for each of the expected entities in a partially observable situation.

We can use entailment to collect evidence for alternative narratives.



For example, when considering two competing narratives for a situation, the relations that define the situations can be used as evidence for or against each narrative.

Unfortunately, some relations will be in both narratives (ambiguous).

Other relations may not be observable. We need a mechanism to reason with unobservable and ambiguous evidence.

Narrative Reasoning

Bayesian Inference from Partially Observable Narratives



Let N be a partially observable narrative composed of a sequence of situations $\{S_n\}$ defined with an Ontology composed of a set of relations $\{R\}$ defined over entities $\{X\}$ represented with Concepts $\{C\}$. We are interested in calculating the likelihood for the narrative given observations of Relations from partially observable Situations within the narratives.

Let $\{X\}$ be the set the entities (instances of concepts) that define the situations. The set of relations $r(X) \in \{R\}$ are defined over subsets of one or more entities $X \subset \{X\}$ from the situation.

Observations of relations from $\{R\}$ provide evidence for or against the narrative. We can include in $\{R\}$ a relation Exists(X) for each entity.

In order to apply Bayesian reasoning, we will replace the Boolean predicates that define relations with probabilistic predicates, $P(r)$. This allows us to define:

$$P(S|r) = P(S) \frac{P(r|S)}{P(r)}$$

The probability for a narrative is the product of the probability for its component relations.

$$P(S|\{R\}) = \prod_{r_n \in \{R\}} P(S|r_n)$$

Our task is made difficult because some of the entities may be unobservable, rendering the relations unobservable. In some cases entire situations are unobservable.

We need to account for both the unobservability of a relation and the observation that the relation is not valid.

Absence of evidence is not evidence of absence!

Narrative Reasoning

Products are not so convenient for accumulating sparse evidence.
To handle this, we will work with Logarithms.

Let $r \in R_s$ be the relations that define the situation.

We will drop the argument (X), for notational simplicity. You can read r as $r(X)$

Let $P(r)$ be the probability that we have observed relation r .

Let $P(S)$ be the probability of situation S .

$$P(r) \cdot P(S|r) = P(S) \cdot P(r|S)$$

and

$$P(r) \cdot P(\neg S|r) = P(\neg S) \cdot P(r|\neg S)$$

$$\text{thus } \frac{P(S|r)}{P(\neg S|r)} = \frac{P(S) \cdot P(r|S)}{P(\neg S) \cdot P(r|\neg S)}$$

The a-priori odds of a situation S are defined as $Odds(S:\neg S) = \frac{P(S)}{P(\neg S)}$

The conditional odds for the situation are $Odds((S:\neg S)|r) = \frac{P(S|r)}{P(\neg S|r)}$

Thus: $Odds((S:\neg S)|r) = Odds((S:\neg S)) \cdot \frac{P(r|S)}{P(r|\neg S)}$

The ratio $\frac{P(r|S)}{P(r|\neg S)}$ is called the conditional likelihood of r .

$$L_r = \frac{P(r|S)}{P(r|\neg S)}$$

Thus the conditional odds for a situation are

$$Odds((S:\neg S)|r) = Odds((S:\neg S)) \cdot L_r$$

The conditional odds for a situation are the a-priori odds times the conditional likelihood for observing the relation.

Narrative Reasoning

Evidence for a Situation

Let us define the “evidence” E_r for a situation as the log of the conditional likelihood.

$$E_r = \text{Log}(L_r) = \text{Log}\left(\frac{P(r|S)}{P(r|\neg S)}\right) = \text{Log}(P(r|S)) - \text{Log}(P(r|\neg S))$$

Observation that an entity or relation is present is positive evidence FOR the situation.

Positive Evidence: if $\text{Log}(P(r|S)) > \text{Log}(P(r|\neg S))$ then $E_r > 0$

Observation that a relation is NOT present is negative evidence against the situation.

Negative Evidence: if $\text{Log}(P(r|S)) < \text{Log}(P(r|\neg S))$ then $E_r < 0$

Inability to observe evidence has no impact.

Absence of Evidence: if $\text{Log}(P(r|S)) = \text{Log}(P(r|\neg S))$ then $E_r = 0$

Notice the difference between “absence of evidence”, and “negative evidence”.

“Negative Evidence” means that an observation indicates that the relation is NOT present in the situations of the situation.

“Absence of evidence” means that it was not possible to observe whether the relation was present or not. This is the case for non-observable situations.

Accumulating evidence for all of the observable relations provides evidence for the situation.

Let us define the a-priori Belief for a situation as the log of the odds for the situation.

$$B_s = \text{Log}(\text{Odds}(S : \neg S))$$

The a-priori Belief is a sort of “bias” for or against believing that the situation has occurred and thus for believing the narrative.

This belief can be influenced by accumulation of evidence: $B(S|\{E_r\}) = B_s + \sum_{r \in \{R\}} E_r$

Narrative Reasoning

Finally, the belief for a Narrative is the sum of the beliefs (log-odds) for the situations that make up the narrative

$$B(N|\{E_r\}) = B_N + \sum_{S \in N} B(S|\{E_r\})$$

Where B_n is an a-priori belief for the narrative.

Note that if a relation is unique to a single situation, then the probability $P(r|\neg S) \rightarrow 0$

And $L_r = \frac{P(r|S)}{P(r|\neg S)} \rightarrow \infty$ and thus $E_r \rightarrow \infty$

If the relation is in many situations, $L_r = \frac{P(r|S)}{P(r|\neg S)} \rightarrow 1$. $E_r \rightarrow 0$

If the relation is never in the situation, $L_r = \frac{P(r|S)}{P(r|\neg S)} \rightarrow 0$. $E_r \rightarrow -\infty$

The "weight" of the evidence depends on the uniqueness of the relation or entity.

However, there may be unknown situations in which the relation exists. To protect from unknowns it is recommended to bound E_r within finite limits.

Affective Bias

If humans were rational, than the a-priori belief for a narrative would be based only on probability.

$$B_n = \text{Log}(\text{Odds}(N : \neg N))$$

Unfortunately, humans tend to add an additional bias based on whether the narrative causes pleasure or displeasure. This is sometimes referred to as an affective bias: B_A

$$B(N|\{E_r\}) = B_A + B_N + \sum_{S \in N} B(S|\{E_r\})$$

The affective bias can lead to choosing false narratives because they please, and rejecting likely narratives because they displease.

Narrative Reasoning

Causal reasoning with narratives.

Causality is an abstraction that indicates how the world progresses.

Defining Causality as a technical term is difficult because the word has divergent definitions in scientific and philosophical domains, in particular because of different notions of agency or action.

Causality assumes notions of time, state and process. A process is a temporally ordered sequence of states (situations).

Causality can be defined as actions or events (the cause) that change a process (the effect). The Cause is said to be partly responsible for the effect, and the effect is partly dependent on the cause.

Processes can have many causes, which are said to be causal factors. All causal factors are prior (before) the process. An effect can in turn be a cause of, or causal factor for, many other effects, which all lie in its future.

Narratives allow us to reason about alternative causes for a situation, where the causes may be random events or deliberate actions.

Reasoning about Causality with Narratives.

In terms of narratives, a Cause is an event or action that changes the evolution of the narrative.

Consider the following example.

Situation 1: John walks to the tramway-stop from 7:20 to 7:30

EventA: John boards the tram at 7:30

EventB: John fails to board the tram at 7:30.

Situation 2A: John is at campus from 7:50 to 9:00

Situation 2B: John is at campus 8:00 to 9:00

We can say that not boarding the 7:30 tram **caused** John to arrive at 8:00.

Events, in this formalism, can be replaced with actions.

For example, maybe John decided not to board the tramway at 7:30 because it was too full.

Events can also be random and non-deliberate.

For example, maybe John tried and failed to board the tramway at 7:30 because it was too full.

Causal Reasoning with Graphical Models

A causal diagram is a graphical tool that enables the visualisation of causal relationships between variables in a causal model. A typical causal diagram will comprise a set of variables represented by nodes. Any variable in the diagram should be connected by an arrow to another variable with which it has a causal influence - the arrowhead delineates the direction of this causal relationship, e.g., an arrow connecting variables A and B with the arrowhead at B indicates a relationship whereby (all other factors being equal) a qualitative or quantitative change in A may cause change in B.