An Analysis of Frame Semantics of Continuous Processes

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Abstract

Qualitative Process theory provides a formal representation for human-like models of continuous processes. Prior research mapped qualitative process elements onto English language constructions, but did not connect the representations to existing frame semantic resources. Here we identify and classify QP language constituents through their instantiation in FrameNet frames to provide a unified semantics for linguistic and non-linguistic representations of processes. We demonstrate that all core QP relations can map to FN, though larger QP evoking phrasal constructions do exist outside of this mapping. We conclude with a corpus analysis showing that these frames occur in natural text involving a variety of continuous processes.

Keywords: Frame Semantics; Qualitative Reasoning

Introduction & Background

Daily life requires interacting with, and reasoning about, continuous processes. They can be as common as coffee flowing into your mug or as abstract as economic growth. Despite their mathematical complexity, people rapidly generate predictions based on mental models of these situations. Forbus' (1984) qualitative process (QP) theory provides a formal language for representing mental models of continuous systems. QP theory is domain general and there is evidence supporting qualitative models as a mental representation. For example, Friedman *et al* (2011) use qualitative representations to simulate conceptual change, and demonstrate intermediate states of knowledge found in middle-school students (Sherin *et al*, 2012).

An important issue is bridging the gap between these cognitive models of change and purely linguistic models. Doing so illuminates the semantics of continuous processes and lays groundwork for systems that learn from and reason with natural language (McFate, Forbus, & Hinrichs, 2014).

Kuehne (2004) developed QP frames, a frame semantic representation inspired by Fillmore *et al*'s (2001) FrameNet. This approach was expanded by McFate *et al* (2014). While useful, both approaches had limited coverage and did not connect QP frames to existing frame semantic resources. We bridge that gap by providing a QP mapping of specific process types in FrameNet as well as their constraints, e.g. *limit points*, which mark the boundaries of qualitative states. We evaluate our mapping on science texts, but expect our approach to be domain general.

Qualitative Process Theory

In QP theory, changes within a continuous system are always the result of processes. Causality starts with direct influences, which express the relationship between the rate of a process and the constrained quantity. A direct influence provides partial knowledge of a differential equation, where the set of direct influences must be combined to determine derivatives. Indirect influences propagate the direct effects of processes through the rest of a system, by providing partial information about instantaneous (e.g. algebraic) causal relationships. Consider water flow into a tub. A direct influence holds between the flow rate and the amount of water in the tub. An indirect influence holds between the amount of water and the water level. Processes are represented by *model fragments* which describe the participating entities, the conditions under which instances of it are active, and what consequences hold when active. The conditions typically include ordinal relationships involving a quantity and one of its limit points.

A system that acquires model fragments from text could reason about real-world scenarios, predicting, for example, that our tub of water may overflow. However, the incremental nature of language makes extracting complete models from text difficult. We turn to frame semantics to provide flexibility, and view this research as a step towards systems that learn by reading about the continuous world.

Frame Semantics

Semantic frames are conceptual schemas that relate lexical items in a sentence to their role in a semantic description (Fillmore, Wooters, & Baker, 2001). Fillmore *et al's* (2001) FrameNet is a frame semantics for English. FrameNet frames are evoked by a frame-bearing lexical unit (LU). The dependent structures in the sentence form arguments to that frame's frame elements (FEs). For example, the `Motion` frame includes frame elements for the `Source`, `Goal`, and `Theme`. It is instantiated in a specific construction by a frame evoking LU such as the word *fly* in "The bird *flew* to Florida". Here, the NP subject fills the FE of `Theme` and the prepositional phrase fills the FE of `Goal`. The specific grammatical instantiation of these roles is called a *valence pattern* for that lexical unit.

Baker, Fillmore & Cronin (2003) present inter-frame relationships including inheritance and subframe. A frame that inherits from a parent has a corresponding frame element for each element of the parent and can introduce others. The subframe relation allows frames to act as ordered arguments to another frame, forming a kind of script. These relations create a frame-lattice with top-level frames like `Event` and specialized inheritors like `Motion`.

QP Language

Kuehne (2004) recast QP theory in a frame-semantic representation to better handle compositionality in language. Quantity frames fill the argument slots of direct and indirect influence frames. The influences participate in quantity transfer descriptions and process frames which capture the results and activation conditions of a process. We adopt a representation closer to FrameNet's, with influences and quantities related through shared lexical units (see Figure 1) This change from previous work (McFate *et al*, 2014) facilitates extracting partial information when grammatical constructions leave out required roles (e.g. an agent).

Kuehne (2004) identified several patterns that instantiated QP frames, and used them to extract QP frames from text, using neo-Davidsonian lexical representations from the Cyc KB[1]. McFate *et al* (2014) extended this approach and introduced narrative functions (Tomai, 2009) to guide disambiguation. This system was limited by the coverage of Cyc's semantic templates, and it also became evident that a finer-grained set of distinctions would be useful. Integrating QP frames with FrameNet helps solve both problems by providing valence patterns by frame type. It benefits frame semantics by providing representations for mental models.

Next we provide FrameNet mappings for each QP frame: *direct influence*, *process*, *indirect influence*, *quantity*, and *ordinal*. We also discuss how *limit points* are represented.

Unifying FrameNet with QP Frames

Continuous processes are process verbs and nominalized verbs in English. Since direct influences are only allowed within processes, we start with them. The direct influence (DI) frame has `constrained` and `constrainer` entities, constrained and constrainer quantities and quantity types, as well as a `sign`. The constrainer entity is the process itself, and the `sign` indicates the direction of contribution for the rate. We introduce an `agentive causer` FE motivated differences between causative and inchoative constructions, as discussed below.

FrameNet has many frames that instantiate continuous processes and DIs. A straightforward mapping for these frames aligns QP elements to potential FN elements. Figure 1 provides an example of `Fluidic_motion`.

We now walk down part of the FN hierarchy for `Event` verbs, and examine the additional valence patterns at each layer. We begin with a broad distinction between causative (with an agent) and inchoative constructions. For example,

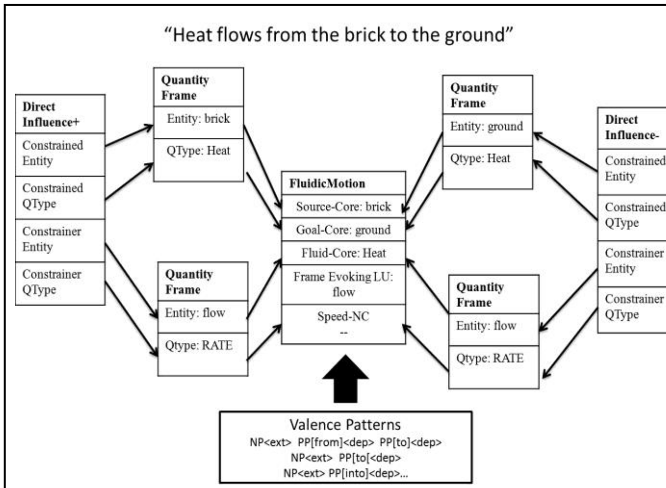

Figure 1: QP frames for a sentence

spill can be causative whereas *flow* is only inchoative e.g.

"The boy *spilled* the juice."

*"The boy *flowed* the juice."

"The juice *flowed* from the box."

While our analysis covers many physical processes, it is not intended to be exhaustive. Instead, it is exemplary of the productivity of mapping these resources.

Inchoative

There is no root frame for all events that don't require an agent. We examine an inheritor of `Event`, `Motion`. We also examine non-agent-requiring state-change frames.

Motion

Basic motion in is captured with the `Motion` frame, which has many inheritors. We use `Fluidic_Motion` as an example. Tables in the following sections illustrate valence patterns for target frames. For example, Table 1 summarizes `Fluidic_Motion` patterns and their alignment to DI frames.

Table 1

Valence Pattern		Example	FrameNet Frames
DI+ NP-V-PP		Water **flows** to the basin.	Fluidic Motion: *Core:* Goal, Source, Path, Fluid, Area *Non-core:* Speed
Cnd-Qtype	Cnd-Ent		
NP<ext>	PP[to]<dep>		
	PP[into]<dep>		
	PP[in]<dep>		
DI- : NP-V-PP		Water **flows** from the basin	
Cnd-QType	Cnd-Ent		
NP<ext>	PP[from]<dep>		
	PP[out]<dep>		

The left-hand column illustrates valence patterns that instantiate the QP elements (here the constrained quantity type and entity). The patterns are presented with FrameNet grammatical functions. The most common are `ext`, `dep`, and `obj` which indicate an external argument (subject), verb dependent, or object. The top left cell of Table 1 says that a positive DI can appear with an NP subject and PP dependent instantiating the quantity type and entity.

For motion, positive direct influences correspond to frame instantiations that include the `Goal` while negative direct

[1] http://www.cyc.com/platform/researchcyc, v4.0

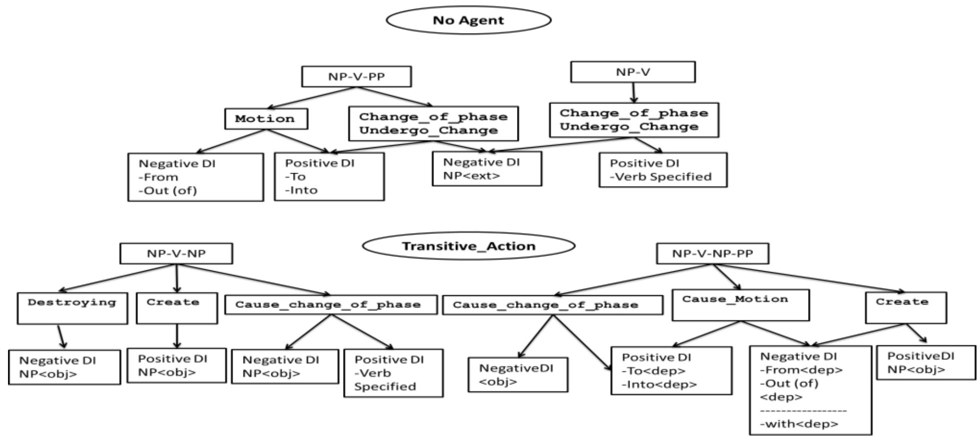

Figure 2: Agentive and Non-Agent Mapping

influences correspond to the `Source` FE. The constrained quantity corresponds to the `Theme` in the `Motion` frame and its corresponding element in the inheritors (ie. `Fluid`).

These can also appear in a single ditransitive prepositional form e.g. “X flows from Y to Z”. Each of the sub-frames that evoke this pattern evokes a DI, but not all possible valence patterns for motion do. For example, `Motion` can have `Path` or `Area` FEs that can occur in isolation e.g.

“Joe ran through the long tunnel”

“Joe ran around the room”

These valence patterns instantiate a motion process, but would require additional sentences to specify a DI.

State_Change & Conversion

State change processes can be represented as a pair of direct influences representing the increase in substance at one phase and decrease in substance at another (e.g. steam and water). This is an important representational decision in because it separates state-changes from their preconditions.

Thus the same NP-V-PP structure in state-change can introduce two influences based on the semantics of the verb (Table 2). FrameNet captures inchoative state-change with the `Change_of_phase`. The core element, `Undergoer`, is the changing entity. This differs from prior analyses of flow and motion, because they are referring to an event without referring to the details of what happened during it (e.g. “The water boils away”).

Table 2

Valence Pattern		Example	FrameNet Frames
DI+ : Resultative-State		The water **froze** to ice.	Change_of_phase: *Core*: Undergoer *Non-core*: Result, Speed, Place
Cnd-QType	Cnd-Ent		
PP[to]<ext>	NP<ext>		
DI- : Resultative-State			
Cnd-QType	Cnd-Ent		
NP<ext>	NP<ext>		
DI- : NP-V		The water **froze**.	
Cnd-QType	Cnd-Ent		
DEN	NP<ext>		

This is clearest in the intransitive where the resulting state, *ice*, is indicated only by the verb, *freeze*. In contrast, intransitive motion may indicate a process but does not specify the predicates (from/to) needed for a full DI. Our conversion interpretation is supported by multiple PP attachments as in “The water froze from liquid to ice”. Thus, our mapping extends the `Change_of_phase` frame to include required initial and final states. This puts our interpretation closer to the `Undergo_Change` and `Cause_Change` frames which include verbs such as *change*, *convert*, and *turn*.

Causative

Causative verbs appear in additional constructions. Many verbs appear in both the causative and inchoative.

We begin with `Transitive_Action` which includes causative frames such as `Cause_Motion` and `cause_Change_Of_Phase`. Each of the verbs under `Transitive_Action` inherits its required `Agent` FE.

`Cause_motion` verbs, with their mandatory `Agent` or `Cause`, appear in additional patterns. For example, the subject of the sentence can be the entity: “The plant creates energy”. Here, the plant does not necessarily gain the energy. It is not the constrained entity of the DI, but its role as agent is vital to the model. This motivates adding an `agentiveCauser` FE which allows for these entity-less causal constructions. These DIs can also appear with prepositional attachments that specify the entity as well as in a passive. (Table 3).

Table 3

Valence Pattern		Example	FrameNet Frames
DI +/- NP V NP PP		New York **pumps** water from the subway.	Cause_fluidic_motion: *Core:* Goal, Source, Path, Fluid, Area, Agent/Cause
Cnd-QType	Cnd-Ent		
NP<obj>	PP[from]<dep>		
	PP[to]<dep>		
	…		
DI+: Passive		Water is spilled from the bucket.	
Cnd-QType	Cnd-Ent		
NP<obj>	PP<from>		

Again, differences in semantic meanings across verbs results in different interpretations of the same construction. `Create` for example, with the preposition *for* creates a benefactive where the entity becomes the PP dependent rather than the NP subject. This same construction leaves the entity underspecified when used with `cause_Motion` or even the `Destroying` Frame. The mappings discussed so far are represented graphically in Figure 2.

Constrainers

So far we have ignored rates. Kuehne (2004) found that English frequently left rates implicit. Non-causative frames above contain the non-core `Speed` FE which includes rate constructions (e.g. at a rate of X per Y). For process frames lacking the `Speed` element, we implicitly encode the rate as the `constrainer quantityType`.

Indirect Influences

The indirect influence frame has a `consequent` and `antecedent` `quantity`, `quantityType`, and `entity`, as well as a `sign`. It maps to the `Contingency` and `Objective_Influence` frames**,** both of which have a frame element corresponding to a causal (antecedent) and dependent (consequent) entity. These LUs can be modified with an adverb such as *negatively* to reverse directionality.

`Contingency` includes verbs like *depend* which use a prepositional attachment to indicate the independent variable. `Objective_Influence` appears in a transitive and passive construction. A similar mapping holds to the `Actor` and `Affected` of the `Causation` frame, as in: “Deforestation causes less carbon to be taken out of the atmosphere.” This sentence indicates a constraint on carbon absorption tied to amount of deforestation. Similar patterns tie the rates of two processes together: “Heating water causes it to boil.” Disambiguating whether the rate or governed quantity is the antecedent frequently requires domain knowledge.

Several phrasal constructions can indicate covariance and thus evoke an indirect influence (Table 4). Construction 1 is the comparative correlative (Culicover & Jackendoff, 1999). Here the first and second phrases map to the antecedent and consequent roles. The sign is given by the directionality of the adjectives. A similar mapping exists for correlative conjunction constructions where, the conjunct phrases both involve change verbs (e.g. increase/decrease).

Table 4

1. Comparative Correlative	The higher the water level in the bucket, the greater the water pressure in the bucket.
2. Correlative Conjunction	Both temperature and pressure increase.
3. As X, Y	As the temperature in the boiler increases, the pressure in the boiler increases.
4. Changes with Y	The pressure of the boiler changes with the temperature.

Quantity Frames

Quantity frames have the required FEs `entity`, `quantity`, and `quantityType`. `QuantityType` relates the frame to the Cyc collection denoting the quantity of the sentence. An example would be *heat* or *pressure*. The `entity` is the object that the quantity attribute pertains to. An optional `quantityValue` and `quantityUnit` FE relate the quantity to numerical data. The optional `signOfDerivative` can indicate a direction of change.

Quantity evoking units include words such as “*heat*” or “*volume*”. These fit best in the `Measurable_attribute` frame, though it has thus far only been applied to gradable adjectives (e.g. the hot brick). Furthermore, in FrameNet the frame explicitly evokes deviation from a norm.

Quantity frames often rely on possession to indicate the entity. These instantiations map to the `Possession` frame and include possessive verbs (e.g. *have*) and genitive constructions, though only a subset of `Possession` verbs is suitable. A counterexample is “The brick owns mass.”

Containment also links quantities to entities. One can describe the “energy contained in the boiler” or separate out quantities with “the air and water pressure in the container”. These constructions fit into the `Containers` and `Containing` frame.

The `QType` can be compositional with the unit. This occurs in constructions with measurement phrases (Table 5).

Table 5

QValue	Qunit	Qtype	5 **liters** of water	**Measures** *Core*: Count, Entity, Unit
Num.Quant	DEN	PP[of]<dep>		

QValue	Qunit	Qtype	Entity	The wall is 6 feet **tall**	**Dimension** *Core*: Dimension, Measurement, Object
Num.Quant	N<dep>	DEN	NP<ext>		
QValue	Qunit	Qtype	Entity	The 6 foot **tall** wall	
Num.Quant	N<dep>	DEN	NP<obj>		

Qunit	Qtype	**Amount** of water	**Quantity** *Core*: Entity, Quantity
DEN	PP[of]<dep>		

The first example consists of a measurement expression modifying an “of” PP. The next two take a measurement expression and adjective phrase and return either a noun-modifier or a predicate (Fillmore *et al*, 2012). Additionally, *‘amount of’* can be used to explicitly define a quantity.

Fillmore *et al* (2012) also identify a measurement phrase construction specific to rates which consists of a numerator, the definite NP, and a denominator, the indefinite np (e.g. “miles per hour”). Rates can also link to a nominalized process verb (e.g. ‘The rate of flow’). These often anaphoric phrases map to the `Rate_quantification` frame.

Ordinals

Inequalities frequently drive processes. An ordinal frame has the elements, `entity1` and `entity2` as well as a `relation` FE that defines the relation (>, <, =, negligible) between them. Entities in an ordinal share a `qtype`.

The most direct way these appear in language is through gradable adjectives in a comparative construction (e.g. ‘cooler than’ or ‘more cool than’). In FrameNet, these fit best into the `Evaluative_comparison` frame, though it does not include comparative adjectives.

Ordinal frames are also evoked by non-comparative `Measurable_attribute` expressions such as *hot* or *cold*.

There are also several ways to indicate a difference without specifying directionality. These are often referential and fall under the `Similarity` frame (Table 6).

Table 6

Ent1	Ent2	Qtype	The temperature **difference** between the objects	**Similarity** *Core*: Differentiating_fact, Dimension, Entities, Ent1, Ent
PP[between]<dep>	PP[between]<dep>	N<dep>		
PP[between]<dep>	PP[between]<dep>	PP[in]<dep>		
Compound-NP-V			The temperatures of A and B **differ**.	
Ent1	Ent2	Qtype		
PP[of]<dep>	PP[of]<dep>	NP<ext>		
NP-V-PP			The temperatures **differ** between the bricks.	
Ent1	Ent2	Qtype		
PP[across]<dep>	PP[across]<dep>	NP<ext>		
PP[between]<dep>	PP[between]<dep>			
PP[from]<dep>	PP[from]<dep>			

One significant difference between our representation and FrameNet's is that FrameNet provides the `Entities` FE which groups multiple individuals to fill one role. We separate them since they indicate different quantity frames.

Limit Points, Transitions, and Constraints

Limit points are quantities that define a value where a model fragment changes status (e.g. *boiling point*). Frequently they occur as a compound noun consisting of a constrained process and a barrier. They can also include numerical values, and participate in possession and containment. Limit points are also evoked with `Extreme_value` adjectives such as maximum or minimum as well as verbs that signify arrival at a point as in the `Arriving` frame.

Many limit points are left implicit or referred to only as a deviation from the norm as in: "The water gets cold which causes condensation" These limit points can be made explicit with a modifier such as *enough* (`Sufficiency`)

FrameNet's `Process` frame has sub-frames indicating different states. Starting conditions are captured with patterns from the `Process_start` frame which includes verbs such as 'begin'. Similar frames exist for stopping, continuing, pausing, and resuming. When used in conditionals, lexical units evoking sub-frames and limit points define the constraints of a model fragment (Table 7).

Many frames in FrameNet can indicate their own activation conditions. Consider the `Cause_Motion` valence patterns in Table 2. The required `Agent` can be replaced with a non-animate `Cause` and viewed as preconditions:

"A temperature difference drives heat to the brick."

These constructions can also be used to elaborate on previous instantiations of frames that they are causative of.

"A temperature difference drives heat flow."

Table 7

Condition	Process	Once the submarine **reaches** crush depth, compression **begins**.	**Process_Start** *Core* Unxp: Event *Non-Core*: Time **Arriving** *Core:* Goal, Theme
PP[after]<dep>	NP<ext>		
PP[when]<dep>			
PP[if]<dep>			
PP[once]<dep>			
Condition	Process	After **reaching** 2,070 degrees, the steel **begins** melting.	
PP[after]<dep>	Vping<dep>		
PP[when]<dep>	VP[to]<dep		
PP[if]<dep>			
PP[once]<dep>			

Explicit `Causation` verbs and modifiers can also indicate a process constraint (e.g. 'because the temperatures differ…').

Finally, quantities within a process can be constrained at certain values using correspondence statements such as:

"The force of the spring is zero when the block is at zero."

This temporal correspondence is captured by the frame `Temporal_collocation`. This frame is vast and includes indexical terms such as "today". We constrain our mapping to patterns that relate two events (e.g. the adverb '*when*').

Corpus Analysis

We have demonstrated that the core elements of QP theory each correspond to FrameNet frames. Next we use a corpus analysis to evaluate the frequency of these patterns in natural language descriptions. We predict that descriptions of continuous processes are prevalent in natural language, especially in explanatory texts. Furthermore, if frame-semantics captures core QP representations, then we would expect that a large number of these descriptions conform to our frame-semantic analysis.

Our corpus consisted of grade school science topics from the Simple English Wikipedia: full articles on the water cycle, condensation, and Bernoulli's principle as well as the first 6 sections about the sun and introduction of the global warming article. There were a total of 90 sentences. Each sentence was annotated for any QP frames. For each process evoking LU (e.g. *flow*) we further evaluated its FrameNet entry. An LU did not have to result in a DI to be counted; it could be an elaboration of a process (e.g. "condensation occurs when…"). We counted FN as having the valence pattern if the specific LU in the correct frame had the complete pattern annotated either alone or as a part of a larger pattern with the same core elements. We also evaluated if the frame-type was analyzed in this paper or one of its children. The results are summarized by article in Table 8. Out of all 90 sentences, 56 (62.2%) had QP material. We identified 53 total process evoking lexical units (e.g. *flow*).

These results suggest a substantial number of sentences in science texts convey QP information, consistent with our prediction. Furthermore, we found that 43.4% of process evoking units already had their specific valence pattern annotated in FrameNet. Thus, mapping QP theory, and possibly other non-linguistic representations, to FrameNet

Table 8

Corpus Analysis Results				
	QP Evoking	Process Evoking LUs	Valence in FN	Type Analyzed
Water (15)	9 (.6)	8	6	4
Sun (28)	15 (.54)	20	10	11
Bernoulli(14)	11 (.79)	5	2	3
Global-warming (21)	13 (.62)	9	4	3
Condensation (12)	8 (.67)	11	1	8

can reveal how these models are expressed linguistically.

Finally, 29 of the 53 process evoking units either directly evoked or evoked inheritors of the set of process frames analyzed above (see Figure 2). The remaining verbs evoked: `Giving`, `Receiving`, `Gathering_up`, `Arriving`, `Expansion`, `Emanating`, `Emitting`, `Departing`, `Soaking_up`, `Using_resource`, `Removing`, and `Fire_burning`. Extending to these additional frames is future work.

Like in Kuehne's (2004) analysis, we found that reference to an explicit rate was rare, only occurring in four sentences of the Bernoulli article. Furthermore, we found no compound-noun limit points (e.g. boiling point) but did find constraints based on deviation from the norm (e.g. when it gets cold…). In part this was due to choice of articles, e.g. articles on boiling or phase changes per se do mention them.

Related Work

Our work dovetails nicely with work in semantic role labeling. General frame semantic parsers such as Das *et al*'s (2014) SEMAFOR could provide FrameNet parses to be generalized using our mapping. Furthermore, knowledge of constraints on qualitative models could resolve ambiguities in language processing as in McFate *et al* (2014).

Ovchinnikova *et al* (2010) used a data-driven analysis to cluster and enrich FN frames about medical treatment. A similar approach could be used to extend our mapping.

Finally, while we've focused on lexicographic descriptions, we identified multi-word and phrasal patterns for indirect influences and quantities, and expect more. These are beyond the initial goal of FrameNet. Fillmore, Lee-Goldman and Rhodes (2012) propose a method for extending FN to include such structures.

Conclusions and Future Work

Much remains to be done. Our corpus analysis suggested additional frames that could be mapped to QP theory, and a larger corpus would both illuminate new frames and establish their frequency. We also hope to use this analysis to enrich the coverage of McFate *et al*'s (2014) system by automatically extracting valence patterns from FrameNet. Future work must also examine how pragmatic and narrative constraints influence QP frame instantiation.

Qualitative Process Theory provides a formalism for representing mental models of continuous processes. While preliminary, by linking this formalism to frame semantic resources we enrich the linguistic representations with a higher-order inferential model and provide a resource that facilitates interactive learning of these models in the future.

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