A vector-based representation of dispositions with an application to modeling fragility of oil and gas pipelines

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Abstract

Current approaches to representing dispositions are quite extensional. The definition of a disposition under such approaches relies on listing all its possible (types of) stimuli and their corresponding (types of) manifestations. Those definitions do not provide suitable frameworks to relate and compare dispositions nor to handle implementation issues about associating the dispositions on some conceptual model with the underlying domain data. At the same time, dispositions have significant similarities to qualities: both are reified properties of enduring entities and are modeled as dependent entities in top-level ontologies. Unlike dispositions, qualities have received truly computational treatments over the last decades, with implementation concerns like mappings to datatypes and object attributes. On the other hand, prominent dispositional accounts of causation rely on interpreting dispositions as *vectors of change*. This approach has not yet been ported into conceptual modeling and ontology engineering. We propose here a framework for relating dispositions and qualities, mapping dispositions to vectors over quality dimensions and discussing the computational advantage of this option. Those vectors describe the path to be taken by a focal quality in the event of the disposition's manifestation. This approach enables matching dispositions to structured datatypes and an intensional representation of dispositions rather than the currently prevailing extensional representations. We apply our approach to the problem of modeling pipeline fragility in the domain of the petroleum industry, a problem of great significance for both the economy and the environment.

Keywords

Formal ontology, conceptual modeling, dispositions, qualities

1. Introduction

A disposition is a property of an entity to behave a certain way under certain conditions [1]. The entity that carries the disposition is its *bearer*; the conditions for the display of the disposition are usually named its *stimuli* or *triggers*; and the behavior of the entity under those conditions is called the *manifestation* or *realization* of the disposition [2, 3].

Current approaches to the representation of dispositions heavily emphasize stimulus-manifestation pairs. For example, the disposition of *fragility* is commonly defined as the disposition to *break* when *struck*. Under such frameworks, it is hard to compare two dispositions (of the same or of distinct types), especially considering that the characteristics to be compared are usually described not as characteristics of the dispositions themselves but of their triggers or manifestations.

On the other hand, the stimulus-manifestation description also does not aid in identifying sets of dispositions whose manifestations effect change over the same properties of their bearer. *Fragility*, when manifested, changes its bearer's shape. The same is true for the disposition to *stretch* when *pulled* (i.e., *malleability*). However, their definitions based solely on stimuli and manifestations are completely different. It is hard to find the common aspects of both dispositions from only those definitions. For example, those common aspects are important in material science, where materials behave plastically up to a certain point and then break.

In the following sections, we present an approach to modeling dispositions founded on vector-based frameworks of causal reasoning. We define a relation of influence between a disposition and a quality that enables the identification of dispositions acting over the same qualities. Further, dispositions are

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mapped to vectors in quality domains (which we call "impetus") just as qualities are mapped to points (qualia) in those domains. The vectors represent the direction and the magnitude of the change to be brought about by the disposition's manifestation. The mapping to vectors enables the comparison of dispositions regarding the kind and the intensity of the transformation effected by their manifestations.

We apply our approach to the representation of fragility of oil and gas pipelines. This infrastructure is critical for the energetic provision of countless urban centers, however it faces numerous hazards, including natural events such as ground movements and landslides, but also corrosion and the unintentional effects of nearby human activity. Thus, a proper conceptualization of the many factors that influence pipeline fragility and may lead to structural damage is fundamental for the elaboration of prevention and intervention strategies.

The remainder of this paper is organized as follows. Section 2 provides background on subjects connected to our proposal, covering the philosophical and ontological status of properties (2.1), the representation of qualities (2.2) and dispositions (2.3) and an overview of vector-based frameworks of causal reasoning (2.4). Section 3 presents our vector-based approach for modeling dispositions, and Section 4 presents an illustrative example of the fragility of glass, pointing out advantages of the vector representation when it comes to distinguishing similar dispositions and representing multi-track dispositions. Section 5 discusses the application of our approach to the representation of a case study on the petroleum transportation domain. Finally, Section 6 offers some concluding remarks.

2. Background

2.1. Properties, Qualities and Dispositions

Both qualities and dispositions refer to what philosophers call "properties", i.e., entities that can be *predicated* of things [4, 1]. A property is *categorical* if entities exemplify it in virtue of being in a certain way. For example, a ball exemplifies "roundness" simply by being of a certain shape. On the other hand, a property is *dispositional* if an entity exemplifies it by having a disposition of behaving a certain way under certain conditions [2, 3]. For example, certain metals exemplify magnetism by being disposed to attract or repel other magnetic materials.

Philosophers spent decades debating which kind of property is the most fundamental. The extreme positions are *pure dispositionalism*, and *pure categoricalism*. Pure dispositionalism argues that all properties are essentially dispositional because they are fundamentally causal powers, i.e., the effects they can cause are, in some sense, their essences. On the other hand, pure categoricalism argues that properties are essentially categorical (i.e., qualities) because their causal roles are not essential to them [4]. There are also all sorts of positions in the middle ground, which accept the existence of both kinds of entities. One position that has gained traction in the last years upholds the *powerful qualities* thesis, which holds that every property is at the same time categorical and dispositional [5, 6, 7, 8]. Under this view, the choice to represent some property as categorical or dispositional is largely arbitrary.

Although there is no consensus among philosophers on which kind of property has the most fundamental ontological status, in the fields of conceptual modeling and ontology engineering both kinds of properties are pragmatically accepted with some ease. Two of the most widely-used top-level ontologies, the Unified Foundational Ontology (UFO) [9, 10, 11] and the Basic Formal Ontology (BFO) [12, 13, 14], define types for representing both categorical properties (called *qualities*) and dispositional properties (*dispositions*). What is similar between *qualities* and *dispositions* is that they are *dependent entities* since neither can exist without inhering in another enduring entity, its bearer.

The philosophical debate on the fundamental nature of properties highlights the fact that the choice between representing a property as a quality or a disposition is, fundamentally, an ontological commitment to a particular philosophical stance regarding the domain to be modeled. Although *color* is usually modeled as a quality, it would be accurate to say that *color* is the *disposition to reflect certain frequencies of light*. Both can be useful definitions under the right context. *Color-as-quality* is useful, for example, for catalogs, inventories, online shopping, and so on. However, for rendering computer graphics through ray tracing, *color-as-disposition* is more useful. Thus, the choice should depend on what makes more sense for a given domain.

2.2. Representing Qualities

According to [15], qualities have their values (*qualia*) in abstract structures called *quality dimensions*. A quality dimension is a *geometric space*, i.e., a mathematical set endowed with additional structure, such as notions of *distance* (in which case the quality dimension is a *metric space*) and *neighborhood* (in which case it is a *topological space*). Two quality dimensions are *separable* if an object may have a value in one of them without having any value for the other. Dimensions that are not separable are said to be *integral*. A set of integral quality dimensions that are separable from all other dimensions is called a *quality domain*.

Quality domains determine the possible values the instances of their associated qualities may take [9, 10]. For example, the color quality is frequently associated with a structure consisting of three dimensions: hue (an angular coordinate), brightness, and saturation (both isomorphic to a positive number line). An object cannot have a certain hue without also having a particular brightness and saturation. The quality domain also determines the relations between its dimensions: for very large or very small values of brightness, saturation gets ever more restricted, as the color tends toward white or black; for small values of saturation, hue becomes less distinct as all shades approximate grey.

At each moment in time, a quality instance is related to a particular point in the associated domain, called its *quale* [16, 17]. Thus, an entity may present changes in its qualities by virtue of them relating to distinct points on the associated domain over time.

A computational approach to qualities may represent each quality dimension associated with a quality as a datatype with corresponding attribute functions that map instances of that quality to their respective qualia in the associated datatype [18]. Operators over that datatype represent the relations constraining and informing the geometry of the quality dimension.

In a similar manner, mappings between quality domains become mappings between distinct datatypes so that the same entity in reality may receive distinct representations in an application. Those representations may be translated back and forth by domain-dependent operations, such as unit conversion between a certain height in feet or meters or a color in RGB (*red, green, blue*) versus HSB (*hue, saturation, brightness*) [19].

2.3. Representing Dispositions

Attempts at representing and formalizing dispositions usually start by identifying their stimuli and manifestations. However, everyday language refers to most dispositions by names that make no reference to their stimuli and manifestations. Examples include fragility, solubility, malleability, flammability, and so on. Nevertheless, those conventional names of dispositions are not very useful to analyze the underlying dispositional structure [20].

Therefore, it is usual to distinguish two distinct ways to refer to dispositions. A *conventional* disposition ascription is expressed with no explicit reference to the stimulus conditions and characteristic manifestations of the disposition in question. A *canonical* disposition ascription, on the other hand, is explicit about its stimuli and manifestations. Canonical disposition ascriptions usually follow the pattern *the disposition to x when y*, where x is the disposition's manifestation and y is its triggering situation. Examples include the disposition to break when dropped, the disposition to dissolve when put in water, the disposition to catch fire when ignited, and so on.

After making this distinction, [1] divides the matter of disposition analysis in two issues: 1. to provide a conceptual analysis of *canonical* dispositions, and 2. to explain *conventional* dispositions in terms of canonical dispositions. The second issue is usually dealt with by identifying conventional dispositions with corresponding (groups of) canonical dispositions. A conventional disposition that corresponds to more than one stimulus-manifestation pair is called a *multi-track* disposition.

Looking at how top-level ontologies deal with this issue, we already noted that both UFO and BFO provide tools for representing dispositions. Most other top-level ontologies, such as DOLCE and YAMATO, do not provide formalization for dispositions. In the case of DOLCE, the lack of formalization reflects the position that the distinction between dispositional and categorical properties is "not reflected, at the ontological level, in a distinction among specifically dependent continuants of different kinds" [21]. On the other hand, some research papers using YAMATO have defaulted to BFO's definition of dispositions [22, 23]. Thus, we shall look into the definition of dispositions according to BFO and UFO, and discuss the similarities and distinctions to each other and to our approach.

BFO defines dispositions as *realizable entities.* Realizable entities are *dependent continuants* that inhere in a bearer and that can be realized in associated processes in which the bearer participates. A disposition type is associated with one or more characteristic manifestation process types and possibly with characteristic trigger process types [14, 24]. BFO also introduces the notion of *reciprocal dependence* between dispositions, i.e., when those dispositions cannot exist in the absence of each other. Reciprocal dependence may be specific (a key's *locking capability* and the *locking susceptibility* of a *single* particular lock) or generic (a ruler's *measuring capability* and the *measurability* of any physical object) [12, 14, 25, 26].

In UFO, dispositions are *existentially dependent endurants* (in UFO terminology, *tropes*) that are only manifested in particular situations, through the occurrence of events [11]. A situation triggers an event when it activates a disposition that is manifested by that event. Two or more dispositions are considered *mutual activation partners* if they are such that all their mutual activation partners must be present in a situation in order for them to be activated [27].

Thus, current top-level ontologies provide significant tools to represent canonical dispositions. At the same time, they conserve the traditional method for explaining conventional dispositions in terms of canonical dispositions. That is, conventional dispositions are usually represented as multi-track dispositions consisting of groups of single-track canonical dispositions.

2.4. Vector-based frameworks of causal reasoning

In a survey of frameworks of causal reasoning, [28] lists three distinct dispositional frameworks: the Mumford-Anjum vector model [29, 30], the two-vector model [31, 32, 33], and the force dynamics model [34, 35]. Although each model draws inspiration from a distinct field, they bear in common the interpretation of dispositions as having directions and magnitudes and, therefore, being able to be represented as geometrical objects with those characteristics, vectors. From the vector representation, the result of the interaction of multiple dispositions may be understood as a function or sum of the vectors of the contributing dispositions.

Force dynamics was developed as a linguistic framework [36] to generalize causative sentences while also including sentences with "despite", "hinders", "prevents", and so on. The generalization is based on identifying two influences over the action described, i.e., the patient's tendency and the agent's action towards or against motion. Those influences are represented as vectors whose directions and magnitudes may be compared. Some examples include:

- *The handrail **prevented** him from falling.* The agent's action against motion is stronger than the patient's tendency toward it.
- *The tall grass **hindered** his walk.* The agent's action against motion is weaker than the patient's tendency toward it.
- *The wind **caused** the ball to keep rolling.* The agent's action toward motion is stronger than the patient's tendency against it.
- *The shed kept standing **despite** the gale.* The agent's action toward motion is weaker than the patient's tendency against it.

Further, experiments involving classifying 3D animations of trajectories determined by force vectors showed that (1) adults can perceive directly the forces that determine distinct types of movement and (2) adults can estimate the result of a combination of several forces of distinct types [34]. The force vectors used also included the influence of social and psychological forces, such as a person's will or the instruction of a law enforcer.

When exposed to the animations, the subjects correctly classified the arrangement of the force vectors under four configuration types, *cause* (where the patient tends against some outcome which is achieved by the agent's action), *enable* (where both the patient and the agent tends toward the outcome), *prevent* (where the patient does not achieve the outcome due to the agent's action) and *despite* (where the agent's action against the patient's tendency to some outcome does not succeed in preventing it). The results indicate that people cognitively understand those kinds of causal relations as a sum of the underlying force vectors.

Therefore, we find support for the vector representation of dispositions in philosophy, linguistics, and psychology. In philosophy, it is founded on the idea that dispositions "point beyond themselves" [24] or are "directed toward" their manifestations [37]. In linguistics, it is evidenced by verbs and conjunctions that describe the interplay of multiple influences under a particular configuration of directions and strengths. Finally, in psychology, the vector representation was shown to model the foundation of certain cognitive processes accurately.

3. A proposal for vector-based representation of dispositions

A disposition is a potential of change. We argue that the main aspects of such change are (1) which aspect of the entity changes, (2) how great is the magnitude of the change, and (3) in which direction the entity changes, i.e., toward what new state. We take the question of *in which aspect* an entity change to be a synonym to the question of *what qualities* of an entity suffer changes. Thus, a disposition is understood as a potential of change of some quality in some quality domain. Regarding the *magnitude* and *direction* of change, we follow the causal reasoning frameworks discussed in Section 2.4 in representing those aspects as a *vector*. We shall call the content of one such vector over a quality domain a disposition's *impetus*. A disposition **influences** a quality by having impetus vectors over the quality domains associated with that quality. Following terminology from [30], we say that the disposition **operates upon** that quality domain.

Definition 1 (Impetus). *An* ***Impetus*** *is a vector representing the direction and magnitude of a potential of change over some quality. Every impetus is member of a vector space over a quality domain. Every disposition has at least one impetus.*

Definition 2 (Operates upon). *A Disposition* ***operates upon*** *a Quality Domain by having a unique impetus in a vector space over that domain. A disposition cannot have more than one impetus in any vector space over a single domain.*

Definition 3 (Influences). *A Disposition* ***influences*** *a Quality if and only if it operates upon all quality domains associated with that quality.*

Under our approach, a disposition manifests when the combination of its impetus vector with those of all present mutual manifestation partners and contributory dispositions results in a vector whose magnitude is sufficiently large so that it crosses a certain threshold in a quality dimension that it operates upon. The combination of all manifestations takes place as an event throughout which the quality or qualities influenced by the disposition follow a path in their associated quality dimensions that is determined by the combination's resulting vector.

The thresholds that must be crossed are not arbitrary; they are part of the geometry inherent to the quality dimension. In metric quality spaces, a threshold could represent a minimally significant distance. In topological quality spaces, the thresholds could signify borders around the distinct neighborhoods.

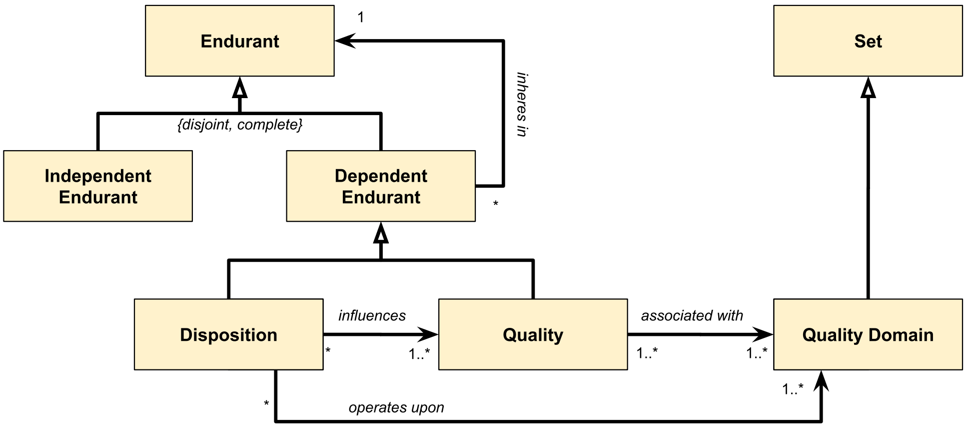

Figure 1: Relations between dispositions, qualities and quality dimensions. Hollow arrows represent subsumption relations.

The approach of relating dispositions to quality dimensions fits nicely into available modeling tools, which currently allow models to semantically relate qualities to the domains where their qualia may be represented, as values of a datatype. Figure 1 depicts the universal-level relations between dispositions, endurants, and quality dimensions. Those relations follow a similar pattern to the relations regarding qualities that are possible to model under current top-level ontologies.

All vector spaces have at least one *basis*, which is a subset of the vector space such that any vector in that space may be written as a sum of the vectors in the basis multiplied by specific scalars. The scalars that multiply the basis components to make up a vector are called its *coordinates* on that basis. Therefore, to represent a vector over some selected basis we only need the values of its coordinates, which can be stored as values of a numeric datatype. We may then describe the combination of distinct dispositions with a mathematical function of their respective vectors.

By assigning an impetus vector over a quality domain to a disposition, our approach also provides a straightforward way to model changes in dispositions, their intensity or direction, by changing its mapping to a distinct vector.

4. Illustrative example: the fragility of glass

What does it mean to say that a glass cup is more fragile than another?

Under current approaches to the representation of dispositions, to compare dispositions of the same type, we must look into either (1) their triggering event, (2) their mutual manifestation partners (or, in a broader sense, the entities present at their activating situation), or (3) their manifestations.

In the first case, one might state that the glass cup that is less fragile is the one that has to *fall from a greater height* in order to break. Or, in the second case, that it has to fall on a *harder surface*. Or even, in the third case, one may say that, in situations where the fragility of the other glass cup would manifest by *breaking*, the fragility of the glass cup that is less fragile would manifest by simply *cracking*, or not manifest at all.

Nevertheless, this strategy extracts the object of comparison from within the disposition itself and looks for it in the associated (stimulus and manifestation) types. It misplaces the characteristics of the disposition as characteristics of other entities and seeks to explain the disposition through its association with those entities. However, the glass cup is not less fragile by virtue of being related to one stimulus type or another; on the contrary, it is related to a particular stimulus type by virtue of it being less fragile. Thus, the whole situation is presented as its inverse, and relations between dispositions appear as relations between stimulus types – the cart is put before the horse.

On the other hand, by mapping each disposition to an impetus vector, our approach enables the direct comparison of dispositions that influence the same quality by comparing their impetus vectors. Under this framework, a glass cup is less fragile than another due to its *fragility* having an impetus vector of smaller magnitude. At the same time, the information that the less fragile glass cup requires a mutual manifestation partner of greater hardness in order to break is not lost. Naturally, the smaller fragility vector needs to be combined to a larger partner vector in order to cross the threshold between the distinct neighborhoods in the *structural integrity* quality dimension.

Figure 2 depicts a one-dimensional structural integrity quality space divided into four regions or neighborhoods, each representing a distinct value of integrity: *whole*, *cracked*, *broken* and *shattered*. Two distinct glass cups, A and B, have their structural integrity value at the left border of the figure. The impetus vectors of their respective fragilities are represented by arrows departing from the left border towards the *broken* region of the quality dimension. The glass cup A has a greater fragility, depicted as a blue arrow, while glass cup B has a smaller fragility, represented in violet. None of the vectors, by itself, has a magnitude large enough to cross the boundary of the *whole* region. Thus, the fragilities of the glass cups will only manifest when brought together with a manifestation partner with a complementary disposition. Any event that does bring those dispositions together is a triggering event.

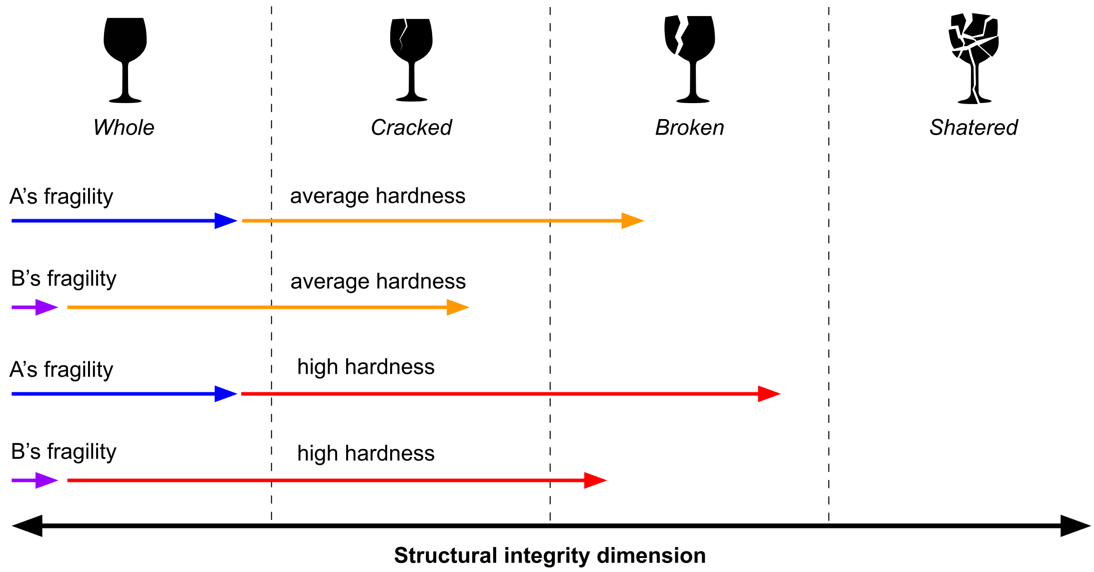

Figure 2: Comparison of the fragility of two glass cups as vectors over a structural integrity quality dimension.

Figure 2 also depicts the combination of the fragility of each glass cup to a complementary disposition of *average hardness* (orange arrow) and another of *high hardness* (red arrow). The combination of the fragility of either glass cup with the high hardness partner is enough to cross into the *broken* region of the quality dimension. Conversely, the average hardness partner only reaches that region when combined with the fragility of glass cup A. Thus, cup B does not break by falling over an average hardness surface.

Further, the vector approach to dispositions allows a simple representation of multi-track dispositions. As Figure 2 shows, the combination of the fragility of glass cup B with a high hardness partner results in a vector that reaches the *broken* region of the structural integrity quality dimension - thus, B's fragility manifests through a *breaking* event. However, when combined with an average hardness partner, the resulting vector crosses into the *cracked* region of the quality dimension, but is not large enough to reach the *broken* region. In this case, B's fragility is not manifested through a breaking event, but through a *cracking* one. This example shows how the vector representation of dispositions enables a multi-track disposition to be characterized by defining a single impetus vector.

On the other hand, if we were to represent the same disposition (B's fragility) under approaches based on stimulus-manifestation pairs, we would need to define 1. a *high hardness* disposition type, 2. a *breaking* event type, 3. a disposition d_1 defined in terms of the *high hardness* disposition type as its mutual manifestation partner and the *breaking* event type as its manifestation, 4. an *average hardness* disposition type, 5. a *cracking* event type, 6. a disposition d_2 defined in terms of the *average hardness* disposition type as its mutual manifestation partner and the *cracking* event type as its manifestation, and finally 7. the disposition itself, as a mereological sum of d_1 and d_2. The mutual manifestation partner types may, in some approaches, be substituted by analogous situation types or triggering event types.

The *meaning* that is captured by those distinct representations is the same. That is, both representations encode the expected behavior of the glass cup under the distinct situations of falling over an average hardness surface or falling over a high hardness surface. The stimulus-manifestation representation encodes that information in four distinct types (two stimulus types and two manifestation types) and two disposition parts that make up B's fragility, while the vector representation encodes the information in a single vector over a quality domain equipped with an appropriate vector combination function.

Therefore, the vector representation takes advantage of a proper characterization of the quality domain upon which the disposition operates to enable a simple and scalable definition. Further, we highlight that such proper characterization of the quality domain is in any case necessary for all approaches that aim to correctly describe the manifestation of the disposition as an event that effect changes over that quality.

5. Case study: fragility of oil and gas pipelines

Currently, operating oil and gas pipelines around the world cover a total distance of over 414 thousand kilometers [38], enough to circle the Earth ten times. This infrastructure plays a fundamental role in energy distribution, supplying oil and gas from remote extraction and production sites.

However, those pipelines face several hazards throughout their operational lifespans. Many pipelines cross mountainous, rugged or tectonically active areas which are subject to the occurrence of landslides or earthquakes. Aging pipelines are also affected by several corrosion mechanisms that may put the structure in risk. Unrelated human activity may also be a source of danger, such as buildings, construction blasting, and so on, that may increase the surface load near a buried pipeline.

Disturbances on the operation of oil and gas pipelines usually come with economical losses. Additionally, damage to a pipeline may lead to leakage or explosions, causing further losses for society and the environment, and putting lives at risk.

Therefore, the prediction of the risks associated to the operation of pipelines is essential to enable stakeholders to decide whether to halt operation for preventive maintenance, to reduce the pressure of the fluid inside the pipe (also reducing the flow rate) to counteract a partially-degraded state, or to allow operation to continue.

Several works in the field of petroleum engineering aim to calculate the risks related to pipeline operation. Those risks are frequently represented through *fragility curves*. [39] defines the fragility of a degraded pipeline as "the conditional probability of its failure for a given level of internal pressure". Additionally, [40] defines pipeline fragility capacity as "the probability that destruction of a certain level occurs", and further states that it "represents an attribute of pipelines as being able to resist a certain level of destruction". Thus, pipeline fragility has a clear dispositional nature.

5.1. Stimulus-manifestation representation of pipeline fragility

We are interested in how to represent pipeline fragility in conceptual models. Following traditional approaches to representing dispositions, we should start by looking into their stimuli and manifestations. Several works describe the effects of pipeline fragility simply as "failure" [39, 41, 42]. Other works, however, define several distinct failure or damaged states. For example, [43] distinguishes three levels of damage over the pipe: 1. slight damage, 2. extensive damage, and 3. loss of containment. Another work [40] defines five pipeline working states: 1. generally intact, 2. slightly impaired, 3. intermediately broken, 4. severely broken, 5. severely destroyed.

Depending on the chosen approach, we could model pipeline fragility as a single-track disposition with *pipeline failure event* as its manifestation event type; or as a multi-track disposition with a set of possible manifestation types either {*suffering slight damage*, *suffering extensive damage*, *loss of containment*} or {*becoming slightly impaired*, *becoming intermediately broken*, *becoming severely broken*, *becoming severely destroyed*}. Of course, there is some overlap between the occurrences in reality described by those event types. It is not our goal to determine precisely how those event types relate to each other, only to demonstrate the modeling requirements that come with the distinct classifications.

Moving on to the stimulus conditions of the pipeline fragility disposition, the works that analyze the effects of corrosion in aging pipes tend to present those effects as a function of pressure [39, 42]. On the other hand, works that investigate the effects of landslides or earthquakes over pipelines usually relate fragility to the ground movement, using values of peak ground acceleration [40], peak ground velocity [44] or peak ground displacement [41, 43]. At the same time, [41] utilizes four other variables alongside ground displacement to determine probability of failure: burial depth, soil friction angle, pipe wall thickness and pipe diameter. Similarly, [43] uses nine variables besides soil displacement: pressure, temperature gradient (between the fluid and the external environment), slope category, soil profile, soil friction angle, soil cohesion, soil specific weight, cover depth and steel yield strength.

We note that few of those variables are intrinsic to the pipeline, while the majority are extrinsic to it and relate to properties of the surrounding soil or of the transported fluid. Those extrinsic variables must also be considered part of the stimulus conditions. Therefore, we may need a combination of a large number of properties to properly characterize distinct stimulus conditions.

Taking an example from [43, p. 15], where fragility curves for three types of damage occurrence (*slight damage*, *extensive damage* and *loss of containment*) over a particular pipeline are given as a function of soil displacement and temperature gradient for two gradient values (0 °C and 50 °C). Each combination of temperature gradient and damage occurrence type results in a distinct cumulative probability of damage over the displacement. That is, there are six distinct stimulus-manifestation pairs expressing six distinct dispositions.

However, expressing pipeline fragility in terms of those six dispositions still ignores other seven variables that influence the probability of damage occurrence. It also ignores distinct values for the variables under consideration. The number of stimulus-manifestation pairs needed to provide a fine-grained definition of fragility grows exponentially with the number of variables to be considered.

5.2. Vector representation

To model pipeline fragility under the vector representation, we must start by finding out the quality domain it operates upon and understanding its geometry. Figures 3, 4 and 5 represent three distinct pipeline integrity quality domains found in the petroleum engineering literature. We shall refer to each model by the surname of the first author of the cited paper.

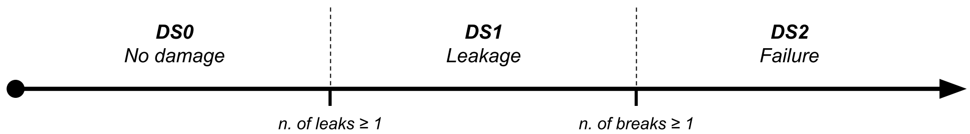

Figure 3: Gehl's pipeline integrity domain, adapted from [44]. Thresholds between distinct neighborhoods are represented by dashed lines.

Figure 3 depicts a one-dimensional discrete quality domain, with a clear notion of neighborhood but not of distance, presented by Gehl et al. [44]. Figure 4 depicts a distinct one-dimensional continuous domain, introduced by Peng et al. [40], that is furnished with notions of distance and neighborhood, although the thresholds between the neighborhoods are (intentionally) fuzzy.

Finally, Figure 5 presents two of the three dimensions that make up the structural integrity domain used by Tsatsis et al. [43], composed of a longitudinal compressive strain dimension, a longitudinal tensile strain dimension and a hoop tensile strain dimension. Each of those dimensions is metric (i.e.,

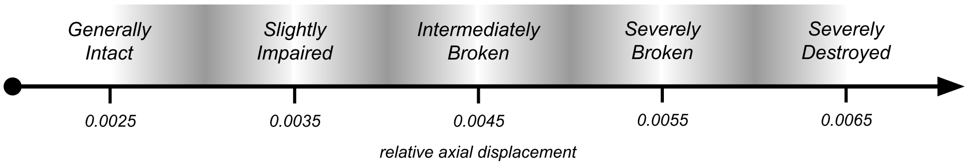

Figure 4: Peng's pipeline integrity domain adapted from [40]. Thresholds between distinct neighborhoods are represented as gradients to indicate fuzziness.

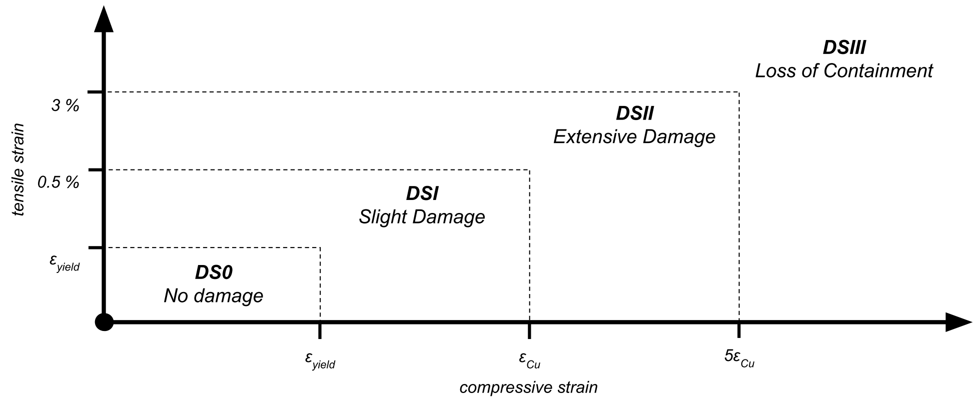

Figure 5: Tsatsis's pipeline integrity domain, adapted from [43]. The full domain contains two tensile strain dimensions, one for longitudinal strain and another for hoop strain.

has a notion of distance) and the domain is divided in three neighborhoods delimited by threshold values in each dimension.

Thus, it is clear that obtaining an appropriate quality domain to utilize in our model does not represent significant extra work - the available literature provides plenty. Figure 6 portrays a conceptual model that includes the distinct pipeline integrity quality domains in relation to a relevant disposition. Enabling the explicit representation of distinct quality domains for the same quality provides a foundation for defining mappings between those domains. In turn, those mappings could allow automatic conversion

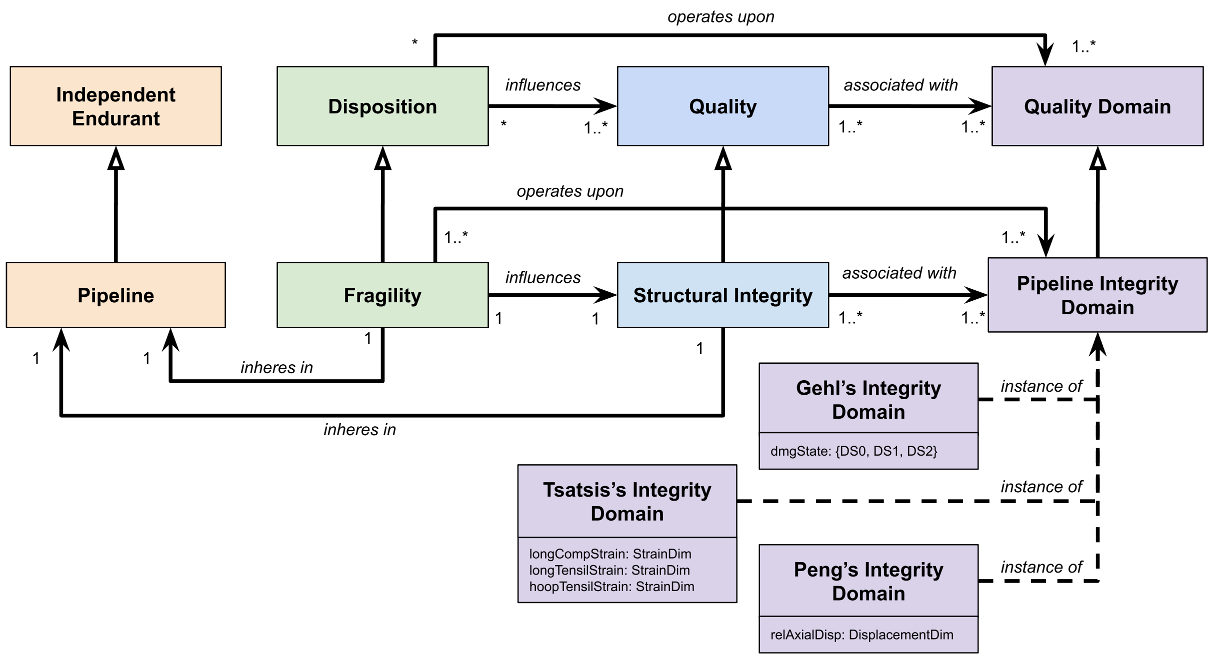

Figure 6: A conceptual model including distinct pipeline integrity domains. Independent endurants are depicted in light orange, dispositions in green, qualities in blue and quality domains in magenta.

of a disposition's impetus vector from a particular quality domain to another, as well as data integration between knowledge bases using representations from distinct domains.

For the sake of providing a more thorough example, we shall use Tsatsis's integrity quality domain, depicted in Figure 5. The domain comes equipped with a mathematical model which describes the interactions of distinct dispositions and may serve as the combination function discussed in Section 3. The extension of the damage suffered by the pipeline depends on several factors pertaining to the pipe, the fluid being transported inside the pipe, and the soil surrounding the pipe, summarized in Table 1, along with the soil displacement produced by a landslide. Mathematical details may be found in [43].

Table 1
Factors that influence pipeline damage occurrence.

Pertaining to the pipe	Pertaining to the fluid	Pertaining to the soil
Pipe diameter Wall thickness Yield strength	Pressure Temperature	Slope category Soil profile Friction angle Cohesion Specific weight Depth

We take those factors to be the causal bases for the pertinent dispositions, and generalize the dispositions inhering in the fluid and in the soil under the disposition type of *stress-inducing capacity*. The *stress-inducing capacity* from the fluid under pressure originates from its expandability, that is kept in check by the pipeline walls, and has the fluid pressure and temperature as causal bases. On the other hand, the *stress-inducing capacity* from the soil comes from its dragging capacity, impelled by some ground movement, and has as causal basis the slope category and the soil's profile, friction angle,

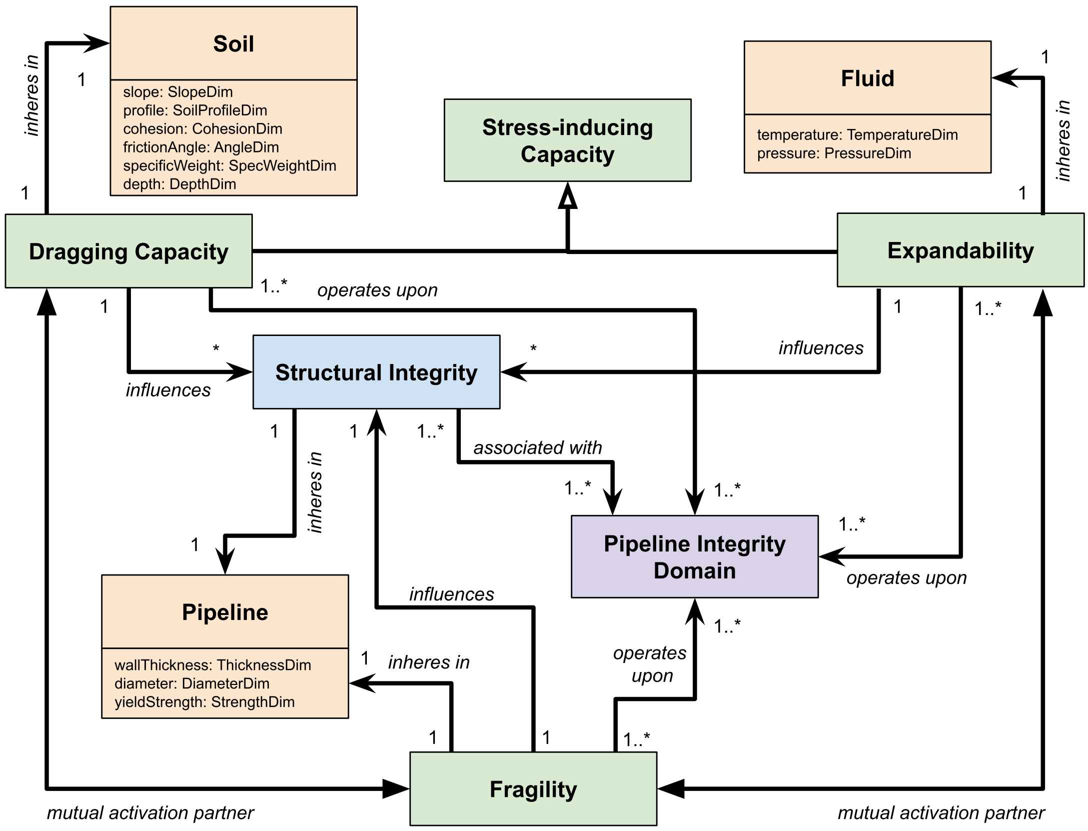

Figure 7: Entities related to pipeline fragility. Independent endurants are depicted in light orange, dispositions in green, qualities in blue and quality domains in magenta.

cohesion, specific weight and depth. The pipeline's fragility, in its turn, has as components of its causal basis the pipe's diameter, wall thickness and yield strength.

Those dispositions are represented as impetus vectors over the pipeline integrity quality domain, pointing away from the origin (i.e., towards the *loss of containment* region). The impetus vectors represent the influence of each disposition over the pipeline's integrity, and how each disposition contributes to the combination function. Each of those vectors may be represented by a set of three numeric values, corresponding to its coordinates on a basis composed of the unit vectors of each domain dimension, i.e., the *hoop tensile strain dimension*, the *longitudinal tensile strain dimension* and the *longitudinal compressive strain dimension.*

Figure 7 presents the entities related to pipeline damage events and depicts their dispositional contact through the *mutual activation partner* relation, which holds between the dispositions types. The dispositional contact between the pipe and the fluid is present for as long as the pipeline is operational. At all times the pressure of the fluid is producing some amount of stress in the pipes. The same is true for the dispositional contact between the pipe and the soil above it, whose weight puts some strain in the pipe even in conventional situations. However, under ordinary conditions, those dispositional contacts do not result in damage to the pipeline as a manifestation of the dispositions. That is the case because the application of the combination function over the impetus of the dispositions does not result in a vector of sufficient magnitude to cross the threshold between ***DS0*** and ***DS1***.

Several occurrences, however, may change this state of affairs. Over time, the effects of corrosion may act to increase the pipeline's fragility, so that it fails under the weight of the soil above it or from the pressure of its load. Otherwise, a blockage may form in the pipeline, leading to an overpressure burst that may be enough to rupture the pipe. Or some landslide over the pipeline may impart energy onto the surrounding soil and temporarily increase its stress-inducing capacity by a multiplicative factor that is proportional to the soil displacement.

6. Conclusion

We put forward a proposal for the representation of dispositions founded on vector-based frameworks of causal reasoning. Such frameworks are founded on philosophy, linguistics, and psychology. In our proposal, the *impetus* of a disposition (i.e., its direction and magnitude of change) is represented as a vector over a quality dimension. Relating a disposition to an impetus vector enables us to represent changes in the intensity and directions of dispositions.

Our framework provides a foundation for defining comparative relations between dispositions. The most basic of those relations is the one between dispositions that influence the same types of qualities. We may additionally define relations between dispositions based on the *direction* and the *intensity* of their impetus. According to the direction, dispositions might present parallelism, alignment, opposition, or other relations based on the angle between the impetus vectors. According to the intensity, a disposition could be stronger or weaker than another. Those relations could significantly enrich dispositional models, and further implementation may make it possible to detect those relations automatically from the influence over qualities and the mapping to impetus vectors.

Mapping dispositions to impetus vectors may aid in reasoning tasks regarding events and their outcomes. Under this framework, the change suffered by an endurant throughout an event resulting from the manifestation of (possibly multiple) dispositions is a function of the impetus vectors of all involved dispositions. The exact mathematical function should be determined by the mutual relations between the dispositions and by their quality domain. Once defined, the combination function could be automatically calculated and utilized when reasoning about those events.

Our approach bears the necessity of a precise characterization of the quality domain, therefore its use should be based on weighing the trade-off between the complexity of defining the quality domain and its combination function and the complexity of defining stimulus and manifestation types for the domain dispositions. We argue that, for many applications, the quality domain characterization is necessary regardless of the chosen representation of dispositions. Finally, future research must be conducted on the experimental validation of our approach and its application to broader use cases.

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