

# ContoExam: an ontology on context-aware examinations

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**Abstract.** Patient observations in health care, subjective surveys in social research or dyke sensor data in water management are all examples of measurements. Several ontologies already exist to express measurements, W3C's SSN ontology being a prominent example. However, these ontologies address quantities and properties as being equal, and ignore the foundation required to establish comparability between sensor data. Moreover, a measure of an observation in itself is almost always inconclusive without the context in which the measure was obtained. ContoExam addresses these aspects, providing for a unifying capability for context-aware expressions of observations about quantities and properties alike, by aligning them to ontological foundations, and by binding observations inextricably with their context.

**Keywords.** Ontology, UFO, semantic reference space, metrology, examinology, property, quantity, context, context-awareness, measurement, examination

## Introduction

Cyber-physical systems, Internet of Things, smart sensor networks, all generate or manipulate representations of observations of the perceivable or conceivable universe: e.g. patient observations in health care, subjective surveys in social research, dyke stability data in water management. Semantic interoperability of sensor data in such systems (a) is inconclusive without awareness of the context of the observation, and (b) critically depends on the extent to which sensor data are comparable.

The International Vocabulary of Metrology (VIM) [1] covers the basic principles governing *quantities*, *units* and *measurements*. It introduces the concept of *kind of quantity* as foundation for **comparability** between *quantities*. However, in ontological terms a vocabulary represents a thesaurus without automated reasoning support with limited level of detail [26]. We conclude that the VIM lacks accurate support required for software systems to reason about comparability: discerning automatically that width, radius and circumference all represent length. Comparability should be founded on clear ontological distinctions, as opposed to only syntactical conventions as with the VIM. Several ontologies already exist to express measurements, W3C's SSN ontology [2] and NASA QUDT [27] being prominent examples. Although supporting automated reasoning, the semantics of these are only loosely grounded in the VIM. Ontologies that claim to facilitate sensor observations should become genuinely grounded in metrological concepts like the VIM. Moreover, it has been recognised [3]-[5] that the VIM has given little attention to the representation of *examinations* about *properties* that have no magnitude: the gender or mood of a person, or blood type. By definition,

these properties are excluded from **metrology** and the VIM, and addressed by **examinology** instead [6]. The extension to domains where the subject of research is a person and the observations are subjective, e.g. [5], only increases the need for a coherent interpretation between *measurements* of *quantities* and *examinations* of *properties*. Applications require awareness about the ontological difference that constitutes the two. We address how they best be unified in one overarching ontology. We propose ContoExam, an ontology that provides for expressiveness concerning the comparability of sensor data. Plus, observing a single property or quantity is mostly inconclusive if the observation is not considered in the context in which it was obtained: a heart rate reading of 128BPM will have very different meaning for elderly vs. new-borns. ContoExam addresses how observations become contextualized without enforcing a particular ontological commitment on context.

We aligned ContoExam to the Unified Foundational Ontology (UFO) [7] (see Section 1.1). However, since the available tooling is not yet capable of representing all UFO's capabilities, we represented ContoExam itself as a UML-artefact, using UFO profiles from [7]-[9]. Our work mainly contributes to a unifying capability for context-aware expressions of observations about quantities and properties alike. We applied a preliminary version of ContoExam in a mobile platform for body sensors [10], the results of which have been presented in [11] and [12].

Typographically, we apply **bold** font to **emphasize** only, *italics* for an *ontological concept* and the *namespace:term* notation to clarify potential confusion about the various sources for terms, 'namespace' being one out of  $\{v,d,u,p\}$ , referring to the VIM [1], Dybkaers Ontology on Properties (OoP) [4], UFO [7], and Semantic Reference Spaces (SRS) [13]. Terms without namespace refer to ContoExam concepts, and guillemets around a «*term*» indicate foundational alignment.

The paper is structured as follows. Section 1 presents the ontological, metrological and examinological backgrounds. Section 2 discusses ontological distinctions between quantities and properties. Section 3 discusses ontological concepts that are required for the expressiveness concerning comparability. Section 4 elaborates on the ontological grounding of context-aware observations, and Section 5 presents concluding remarks.

## 1. Foundational backgrounds

### 1.1. Ontological foundations

We base our work on the Unified Foundational Ontology UFO [7] that in itself is founded on the 4-category ontology [14]. Dybkaer explicitly adheres to the 4-category view ([4], Sec. 6.14). There are indications that the VIM implicitly accepts this view ([1], Sec. 1.1 note 1). We analysed the VIM and could find no indications that the adoption of the 4-category view will introduce inconsistencies. We state that the 4-category ontology does not conflict with the VIM [1] and OoP [4], and conclude that our attempt to align the amalgamation of the VIM and the OoP to UFO is fundamentally sound [14]. We have chosen UFO over other foundational ontologies such as DOLCE, BFO, GFO, BWW, because of its broadness combined with depth and granularity, its match with the domains of metrology and examinology, and because it is a promising emerging ontological foundation. We adopt, and subsequently extend UFO with the notion of reference spaces, coined by Probst [13], to cater for

**conventional** aspects that form a significant part of metrology and examinology. In this way, ContoExam provides for a highly accurate engineering artefact.

UFO on the one hand differentiates between *sets*, *universals* and *individuals*, and, on the other hand, further classifies the latter two into *substantials* and *moments*. The relation between *moment* and *substantial* is one of **inherence**; a *moment* exists as long as its bearing *substantial* (its *bearer*) exists. For instance, inherence glues being unmarried to a particular bachelor Friedrich, and a particular shade of greenness to my car. Similarly, *moment universals*, a.k.a. *quality universals*, are said to **characterize** *substantial universals*. *Universals* also categorize *individuals*, like being unmarried categorizes bachelors. *Individuals* are instances of *universals*, like Nietzsche being an instance of Person. Furthermore, an *individual x exemplifies* the *universal U* if there exists an *individual moment m* that (i) inheres in *x*, and (ii) is an instance of *U*, e.g., Friedrich exemplifies being unmarried because he bears the property of being bachelor.

### 1.2. Metrological and examinological foundations

In the VIM [1] a *v:quantity* is defined as “property of a phenomenon, body, or substance (...)”. A *property* is being defined [15] as “facet or attribute of an object (...)”. Likewise, Dybkaer [16] considers a *d:property* (and equally so, *v:quantity*)

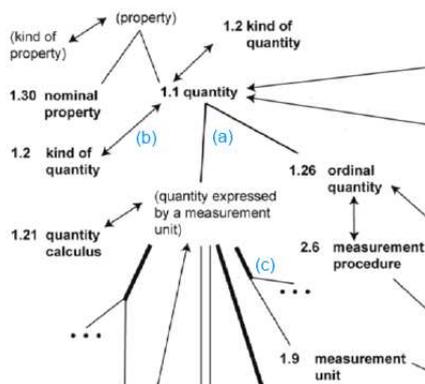


Figure 1 Part of VIM model around quantity (from [1])

“being inherent in a phenomenon, body, or substance”, the latter three termed *d:system*. Our first design rationale therefore is to acknowledge that *d:property* and *v:quantity* **inhere in a *d:system***. Implied by the VIM, and explicitly stated by Dybkaer, is that being examinable is an essential characteristic of a *d:property*, although properties may be assumed to exist without being examined. Our second design rationale is to follow the VIM and Dybkaer to constrain the meaning of *d:property* and *v:quantity* to potentially **being examinable**, directly or indirectly. A third design rationale is to acknowledge that, as raised by metrology [5] and ontology [17], *d:properties* and *v:quantities* are to be treated distinctively. As shown in Figure 1, the VIM excludes, by definition, properties that have no magnitude, termed *v:nominal property*, from *v:quantity*. Both [3] and [4] accept ‘having magnitude’ as delimiting characteristic, distinguishing *v:quantities* from *v:nominal properties*, and, subsequently, *v:measurements* from *d:examinations*. Blood type, mood and gender are examples representing a type of *v:nominal property* that can be *d:examined*, whilst length is considered a *v:quantity* that can be *v:measured*.

## 2. Property versus Quantity in an ontological perspective

Providing for expressiveness for comparability and following our third design rationale implies providing for proper ontological grounds to differentiate between *quantities* and *nominal properties*. The majority of the ontologies (excluding [17]) that represent

sensors or measurements build on the VIM only and, hence neglect our third design rationale. This results in subtle but significant ambiguities that impede truly open sensor networks; e.g., the Semantic Sensor Network (SSN) ontology [2] introduces an inconsistency between a *property* and its *value*[15]<sup>1</sup>, while other ontologies suffer from similar internal inconsistencies, e.g., QUDT [27] can't *d:examine* a *d:nominal property*.

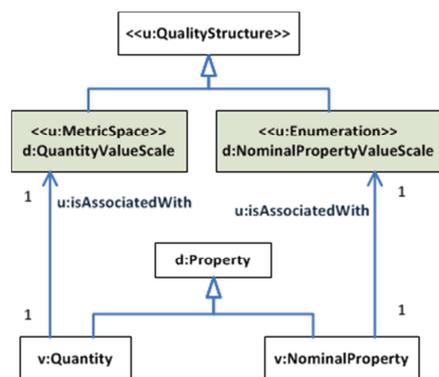


Figure 2 Summarizing ontology around nominal properties and quantities. Gray boxes represent alignments between metrological or examinological terms and UFO groundings.

Since the distinction between *v:nominal property* and *v:quantity* is associated with the presence or absence of a magnitude, we conclude that this distinction should be sought in the characteristic of their *v:value scale*. Guizzardi [7], founded on [18], distinguishes *u:quality universals* as perceivable or conceivable *u:moment universals* that are associated with a single *u:quality structure*: an n-dimensional structure spanning the envelope that is associated with the potential “values” the *u:quality* can exhibit. Moreover, a *u:quality structure* is considered either a *u:metric space* or a *u:non-metric space*, the latter representing, a.o. *u:enumerations*, the former quality structures exhibiting a

distance function to calculate the distance between each pair of values in the structure.

From the above we conclude that in order to differentiate between *v:nominal properties* and *v:quantities* we need to establish their associated *u:quality structures* as «*u:enumerations*» or «*u:metric spaces*», respectively. These concepts are foundational to *d:nominal property value scale* and *d:quantity value scale*, respectively. Clearly, this does not clarify the fundamental distinction; it merely shifts it to their underlying scales. Still we conclude to refer to the similarity between a *v:nominal property* and *v:quantity* by their correspondence to *d:property*, while they differ in their associations to distinct *u:quality structures*, see Figure 2. In Section 3.3 this fundamental difference (their scales) and the grounding of their similarity are elaborated on.

In the remainder we use the term *property* as defined by Dybkaer (*d:property*) to represent the similarity between *v:quantity* and *v:nominal property*. This holds also for composed terms that build upon *property*, e.g., *kind of property* refers to the similarity between *d:kind of property* and *v:kind of quantity*.

### 3. An ontological notion of kind of property

The essential characteristic for a *kind of property* is stated as **having sign of comparable properties** [16]. Dybkaer [4] (and similarly, the VIM) defines a *kind of property* as the “common defining aspect of mutually comparable *properties*”, and analyses that members of the set of *properties* carved out by *kind of property*, belong to a defined class and are mutually comparable by their respective values on a given

<sup>1</sup> In SSN, *property* corresponds to *property* from [14], and thus doesn't exclude having magnitudes, as underlined by aligning it to the DOLCE ultralight (DUL) concept *quality*. Contrarily, SSN's *observation value* of its *property* corresponds with the *v:measured quantity value* that only includes magnitudes.

*property value scale*, see Figure 3. Hence its purpose is to determine whether and how values of *property X* can be combined with values of *property Y*. The underlying nature of (i) the concept of *kind of property*, and (ii) its relation with *property*, remains unclear in [1], [4], [16] and [27]. In [19] it is made clear that the metrological definitions of *v:quantity* and *v:kind of quantity* are not free from ambiguity, and it is analysed that only comparisons between *v:quantities* ‘in the general sense’, e.g., length, must be taken into account in VIM’s definition of the concept of *v:kind of quantities*. We consider it mandatory to clarify how mutual comparability between *properties* of distinct entities can be ontologically established. Simply creating a concept may suffice for modeling comparability yet fails to identify and represent the ontological nature of the ‘common defining aspect of properties’. Consequently, software issues such as interoperability or conceptual modeling will surface sooner or later because they can’t provide for proper matching of ontologies. This will result in inability to establish, for example, the particular green of a car to be comparable to the particular colour of a little black dress but not to its size. Or that body weight (mass) and heart rate (frequency) can be used in a fitness application but height (length) is irrelevant, and, contrarily, that height and weight are purposefully used to derive body mass index.

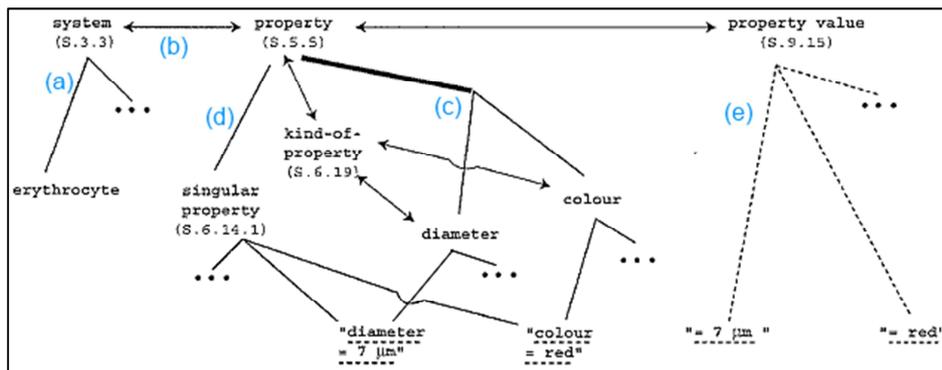


Figure 3. Concept diagram on property, kind-of-property, and value (from[4]). Relationship type as (a) generalisation, (b) association, (c) terminological dimension, (d) instantiation, (e) possible plurilevel generic hierarchy

We therefore strive for an ontological grounding of (i) what it means to be a *kind of property*, and (ii) what its relationship with *property* characterizes.

### 3.1. Comparability, property and kind of property

We observe that the definitions from Section 1.2 are consistent with the view that *property* can only correspond to a *«u:quality universal»*. This conclusion is based on the facts that (i) *u:quality universals* characterize *u:substantial universals*, and (ii) *u:moments* exhibit the characterizing feature of being existentially dependent on another *u:individual*, called the *u:bearer* of the *u:moment*, which is either a *u:moment* or an *u:substantial*. In the context of observations, the subject of observation, i.e, *d:system* aligns with the *u:substantial* that bears the *u:moment*, called a *u:quality*, that is an instance of a *u:quality universal*.

The Semantic Sensor Network (SSN) ontology imports the QUDV ontology [20], thus reusing *v:kind of quantity* in its '*QuantityKind*', and applies a subclass relation with DUL's *quality* concept. However, the relation between both concepts is not further clarified other than that they apparently both align to DUL's *quality* [21]. In [17], the

notion of a *quality role* is suggested in order to differentiate between *property* and *kind of property*: “length (*kind of property*) is playing the *role* of height (*property*) in the context of a human body (*d:system*)”. However, Guizzardi shows in [7] that only *substantial universals* can take on a *role*, and we take the stance that *kind of property* cannot be conceptualised as such since it is not founded on matter nor does it possess spatial-temporal *moments*. We further conclude that although *kind of properties* is about properties, it is not a *property*. This is underlined by the concept diagrams in [1], [4] that consistently refer to the relationship between *property* and *kind of property* as an association (see Figure 3) as opposed to a specialization. Moreover, a *kind of property* can be represented by various *properties*, e.g., length as height, thickness, circumference [22]. In other words, *kind of property* and *property* are genuinely distinct ontological concepts with a 1:n cardinality of their relationship. We further emphasize that a *kind of property* can be represented in various ways. For instance, colour can be represented as red-green-blue (RGB) or as hue-saturation-brightness (HSB) structures. This implies that being comparable is not equivalent to having identical scales or units.

Further to comparability, if we measure the height of a 3D object, we refer to the length of the normal-vector of its horizontal plane, independently on how it was initially positioned. So “height” potentially refers to three distinct vectors. More generally, *properties* such as height, thickness and circumference are dependent on some prescription or instruction, i.e., a convention. If we measure “Nietzsche’s height”, then we take the convention that we measure the *property* defined as the vertical length, i.e., the perpendicular that is set up from the ground plane to the top of his head when he is standing upright – the “length-as-height-convention”. We conclude that *property* only **represents**, somehow, *u:quality universals* but cannot be **aligned** to it in ontological sense as *u:quality universal* lacks convention. Instead we claim that **comparability**, based on the ‘common defining aspect of properties’, finds its origin in the *u:quality structure* and that *kind of property* represents the entity that **refers** to it and hence genuinely aligns with «*u:quality universal*».

In order to more easily elaborate on the nature of *property*, we will first elaborate on the ontological notion on *property value* and *property value scale*.

### 3.2. Property value

According to [7] and [17] and following the conclusion of the previous section, if we refer to “Nietzsche’s height of 1.73m”, then Nietzsche **exemplifies** the *u:quality universal* length, since the *u:individual moment*  $q_1$  of “Nietzsche’s-length-as-height-convention”, termed a *u:quality*, inheres in Nietzsche and is an instance of the *u:quality universal* length. Since identity prevails comparability, if we want to compare the length exemplified by Nietzsche, with the length exemplified by another *u:substantial individual*, say Paris Hilton, then *u:quality* must follow a principle of identification that distinguishes between the *u:moment* (quality  $q_1$ ) that inheres in Nietzsche from the *u:moment* (quality  $q_2$ ) that inheres in Hilton, although both have the same *property value* of “1.73m”. Dybkaer defines *property value* as “inherent feature of a *property* used in comparing it with other *properties* of the same *kind-of-property*”. In this definition, *property value* (“1.73m”), expressed as the product of value and unit, coincides with what is called by Gärdenfors [18] a *u:quale*, which represents the position of an individual quality within a certain *u:quality structure*. This implies that if we want to compare the length of Nietzsche, i.e. the quality  $q_1$  with property value

“1.73m”, with the length of Hilton, i.e. the quality  $q_2$  with property value “1.73m”, we find that, because  $q_1$  and  $q_2$  map to the same region in the *u:quality structure*,  $q_1$  and  $q_2$  share the same quale  $ql$ , representing identical length. As stipulated by [17], this also provides us with the ability to record the change in length between the boy Friedrich and the man Nietzsche because quality  $q_1$  of the boy is, thanks to its principle of identity, the identical quality  $q_1$  of the man, which has one single quale  $ql$  that changes over time. We conclude that the *property value* aligns with a *«u:quale»*.

### 3.3. Property value scales

A *d:property value scale* is defined by Dybkaer as an “ordered set of possible, mutually comparable *property values*”. He brings the two concepts together in a note to the *d:property value scale* as “A *property value* is a member of a conventionally defined set of possible values forming a *property value scale*”. Although this seems ontologically similar to the quality structure, the distinction is in the words “conventionally defined”. There exist many conventionally defined value scales, and new ones will definitely emerge. But they all order the values of the underlying *u:quality structure* in the same (conventionally defined) way. Introduced as semantic reference space (SRS) by Probst [13] shows that there is a fundamental difference between the absolute value, e.g. of the length of Nietzsche, and the way his height is being referred to as “being 1.73m tall”. The former is an absolute physical that can never be established in absolute terms due to inaccuracies that originate in the observation system, random errors etcetera, and the latter is (a) an approximation of the former, and (b) founded on an arbitrary however conventional magnitude chosen as referencing measure of unit, e.g. metres or feet. This implies a separation between the *u:quality structure* of *v:true quantity values* that serves as **conceptualization** of physical reality, and the **representation** of that *u:quality structure* that serves as (i) a partitioning scheme, and (ii) a naming scheme. This representation of the *u:quality structure* is coined by Probst as semantic reference space, or *p:reference space* for short [13]. A *p:reference space* exhaustively partitions the *u:quality structure* by grouping magnitudes in partitions called *p:reference regions*, thereby discretising the *u:quality structure*. A *p:reference region* represents a discrete approximation of the including *v:true quantity values*. A *p:reference region* can be assigned a *p:sign*, such as “1.73m”. But this is not always possible, e.g., in the colour spectrum one can define much more reference regions than can be denoted with a colour name. Still, a single *p:reference region* maps to several *u:qualia* that, by token of the single *p:reference region*, cannot be distinguished amongst each other anymore in that reference space.

A *p:reference space* is not part of a *u:quality structure*, but represents an entity in its own. Still, it is based on a single *u:quality structure*, and, hence, a *u:quality structure* can be represented by many different *p:reference spaces*, depending on the applied schemes (partitioning and naming). However, in order to act as such the *p:reference space* needs grounding first. This implies that a *u:quale* must be chosen (and recognized by a social agent, hence the convention) that serves as anchor for one single *p:reference region*. With this grounding, a measurement process results in the identification of the convention for the *u:quale*, i.e., the *p:reference region*. An elaborated treatise on *p:reference spaces* and *u:quality structures* and the identification and grounding of *v:units of measure* can be found in [13]. In order to provide support for *p:reference spaces* within ContoExam, an extension of UFO was required. We have

provided for such an extension by defining a *p:reference space* as «*u:set*», similar to their definition in DOLCE and to UFO’s definition of a *u:quality structure*.

Founded on the fundamental difference between a *u:quality structure*, defined by nature, and its approximated counterpart, the *p:reference space* defined by convention, we can now provide for an alignment of *v:measured quantity value scale*, e.g., height in metres, and *v:true quantity value scale*, e.g., the absolute length. Where the latter is aligned with a «*u:quality structure*» of unnamed, abstract but ordered magnitudes, the former refers to its discretized, named approximation, i.e., «*p:reference space*». In this way, colour, conceptualized as a *u:quality structure*, indeed can be denoted by multiple distinct (RGB versus HSB) *p:reference spaces*, and length can be represented in feet

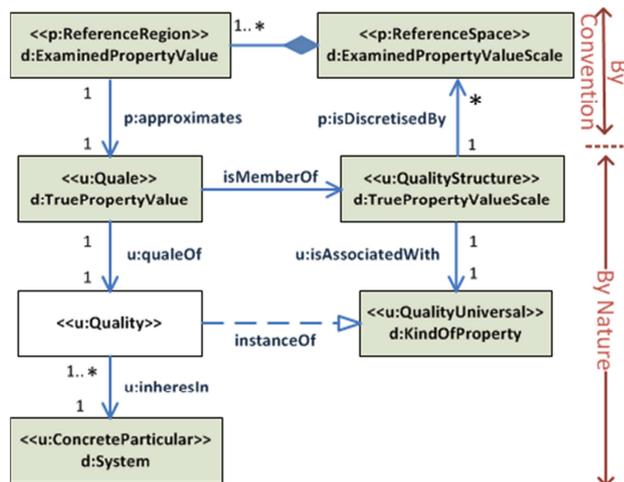


Figure 4 Summarizing ontology around property value scale, and kind of property, aligned to an extension of UFO that includes semantic reference structures from [13]

for height or in  $\mu\text{m}$  for wafer stepper displacements. Since both represent the same quality space, they remain comparable and conversion between the two reference spaces is possible. Indeed, our earlier remark in Section 2 (being comparable is not equivalent to having identical scales or units) still holds since that referred to concepts that, as explained here, have been defined by convention. The results are depicted in Figure 4.

### 3.4. Property and its relation to kind of property

We have found ontological alignment for *kind of property*, how it relates to *property values* and their underlying *property value scales*, and how a fundamental difference between the *u:quality structure*, defined by nature, and the *p:reference space*, defined by convention is foundational to that. This provides us with the material that we need to ground *property*. Considering the conventional nature of a *property*, e.g., height, circumference, we derive that its ontological nature should be sought in close relation to the conventionally defined *p:reference space* that mirrors the actual *u:quality structure*. Just as *kind of property* is associated with the **true property value scale**, we suggest a *property* is associated with the **conventional property value scale**. However, unlike *kind of property* that is instantiated by a *u:moment*, a *property* cannot represent a *u:moment universal* since the convention as such is a social agreement that does not *u:inhere* in a bearing *u:substantial* but represents a substantial, albeit no physical but a social one. In [9] UFO recognises a *u:normative descriptions*, a specialisation of *u:social object* that defines nominal universals that are recognised by at least one social agent, e.g., an organisation or person. We therefore propose to align *property* with *u:normative description* to represent a recognized, nominal universal, e.g., height. Its relation with the conventional *p:reference space* is then represented by a one to one

«*u:is associated with*» relationship that represents the formal correspondence with the *u:association* relationship.

Being a *u:substantial universal*, a *property* instantiates an individual that represents the convention as it has been applied during the *d:examination* and for which just one *p:reference region* takes the role of being the *d:examined property value*. This individual has been called the *d:singular property*, e.g., the radius of circle A,  $r_A$ . This individual opposes the *d:examinand* that represents the property that is intended to be examined and what aligns to the *u:quality*, e.g., the length of a line segment (that is

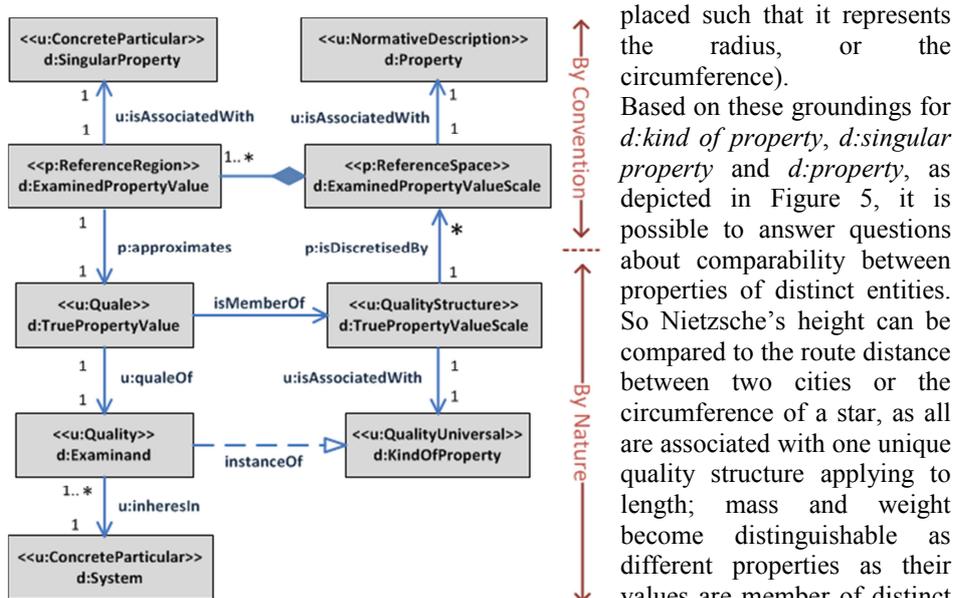


Figure 5 Summarizing ontology around property, kind of property and their relationship, aligned to UFO with SRS extension.

placed such that it represents the radius, or the circumference). Based on these groundings for *d:kind of property*, *d:singular property* and *d:property*, as depicted in Figure 5, it is possible to answer questions about comparability between properties of distinct entities. So Nietzsche's height can be compared to the route distance between two cities or the circumference of a star, as all are associated with one unique quality structure applying to length; mass and weight become distinguishable as different properties as their values are member of distinct quality structures.

### 3.5. Type of scales

The above only refers to quantity and quantity scales. This is because Probst argues that quality spaces, due to their inherent structuring characteristic, cannot apply to *d:nominal properties*. Lacking a magnitude, enumerations are of **nominal** scale, hence values of a *nominal property* (a *d:property* associated with *enumerations*) can only be compared against equality. Contrarily, by virtue of having a magnitude, *quantities* (*properties* associated with *metric spaces*) enable (i) sorting values into a rank (*ordinal* scale, e.g., Mohs scale of mineral hardness), (ii) establishing differences between values (*differential* scale, as °C temperature) or (iii) establishing ratios between values (*rational* scale, as thermodynamic temperature) [1], [4].

Probst argues that quality structures, due to their inherent structuring characteristic, can't apply to *d:nominal properties* as these don't have magnitude and so lack structure. Thus, reference spaces do not exist for *d:nominal properties*. We concur this for *quality universals*, but defend that this is not true for *mode universals* [7]. These are conceptualized as multiple separable quality dimensions, such as symptoms, skills, beliefs and desires [7]. Modes aren't directly related to quality structures but they do represent determinables, which determinates are separable quality dimensions. For instance, blood type is considered as a nominal property built upon red blood cell

surface antigens (quality dimensions) together forming a blood group system. The common grouping types are the ABO and Rhesus, but 31 other groups are recognized. A more complicated example is ethnicity race, for which its underlying quality dimensions are not fully determined (yet). Therefore, the “mode space” (spanned by the separate quality spaces of the separable quality dimensions) possesses a compound structure by virtue of the structure of the underlying dimensions, which may not all known. Besides, absolute quales exist in each of these dimensions, creating the absolute compound quale. Such mode space, as a quality structure, can be represented by partitioning and naming schemes resulting in a nominal reference space. With this argument in mind, we can differentiate between value scales that order magnitudes (*v:quantity value scale*) and those that distinguish nominal values (*d:property value scale*). For reasons of space and simplicity we choosed to merge the two into one generic alignment: *property value scale* aligns to «*p:reference space*».

#### 4. Ontological coherence between measurement, examination and context

##### 4.1. Measurement and examination

As indicated by the VIM (see Figure 6), a *v:measurement* is associated with many entities. Dybkaer defines an *d:examination* as “structured activity [prescribed by examination procedure] giving an examination result”, and adds that it essentially consists in comparing the *d:examinand* with some conventional defined reference.

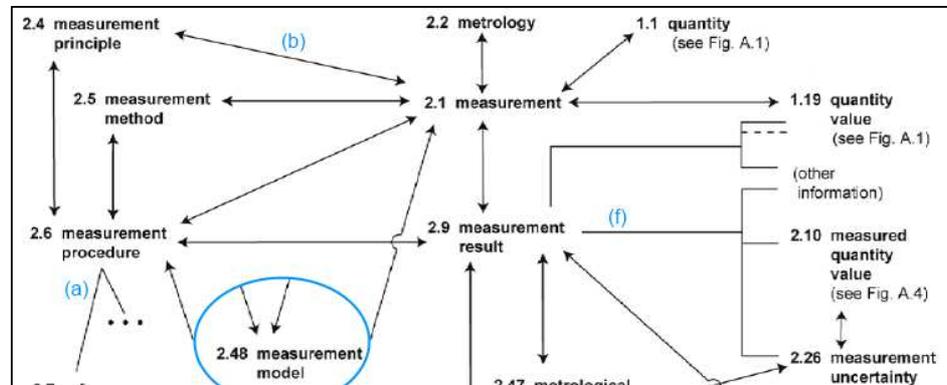


Figure 6 Part of VIM model around measurement (from [1]). Relationship type as (a) generalisation, (b) association, and (f) partition.

In Section 2 we concluded that the distinction between measurement and examination is not in the activity itself, but in the quality structure that is associated with the property under consideration. Similarly, we do not make an ontological distinction between a *v:measurement* and a *d:nominal examination* and are only interested in their unifying entity *examination*. We further analyse that the only entities that are of direct interest to an *examination* are (i) the *d:system*, (ii) the examining system, and (iii) the procedure prescribing the *examination*. Although the VIM doesn't include any direct association of the *examination* with (i) and (ii), we defend that both are necessary participants for performing an *examination*; without their existence, an *examination* can't happen. Regarding (iii) we take the scientific stand that an *examination* must be **verifiable**, and therefore requires a prescribing examination procedure. In line with

Dybkaer we further defend that, following its definition, the *d:examination procedure* is dependent on a *d:examination principle*, *d:method* and *d:model*, thus their association to the examination is consolidated. A dependence on an *d:examination result*, including its value, is similarly consolidated through *d:examination system*. Since we already established that a *kind of property* inheres on *d:system*, by admitting an examination's dependency on the latter the former is implicitly included.

UFO ontologically discerns enduring from perduring substantials. Endurants **are in time**, as opposed to perdurants that **happen in time** and accumulate temporal parts that do not persist [9], [22]. *Perdurants* represent events, e.g., a kiss or a solar eclipse, and their existence is bounded by a time interval: a region in a temporal *u:quality structure*. As to its temporal characteristic we consider a *d:examination* a perdurant: although its results remain, the examination itself ceases to exist and can only be repeated. Since it requires participation of three substantials (*d:system*, *d:examination procedure*, and *d:examination system*), it should be considered a **complex** perdurant, i.e. composed of two or more perdurants. Furthermore, by virtue of its intention to obtain a *d:examination result*, we align the *d:examination* to «*u:complex action*» because *u:actions* represent intentional events that lead to a post-state situation satisfying that intention. Finally, perdurants enter into relation with endurants as *u:resource participants*. Figure 7 depicts the resulting alignment.

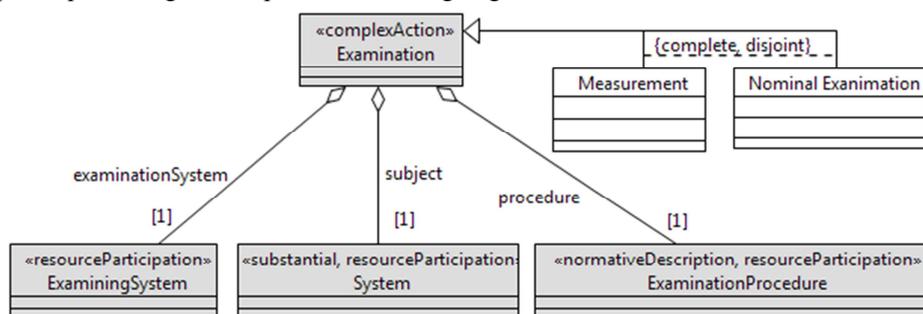


Figure 7 Excerpt of the ontology around examination, aligned to UFO

#### 4.2. Context-aware examinations

To make applications distinguish between the 80BPM of a walking woman from the 80BPM of a sleeping new-born, we differentiate the **context** of an entity, e.g., a person walking, a female person and a person with 80BPM heart rate, from the **situation** that the entity is in: a walking female with a heart rate of 80BPM. We differentiate the term **context** from the usual notion on context that is more similar to the above **situation**. This approach is taken from [23] that reports on the foundational language constructs required to construct context: concepts *entity* and *context*, the latter representing what can be said about the former, however without any ontological commitment assuming primary context types such as in [24]. The authors differentiate between intrinsic and relational context: intrinsic context inheres in one entity only, e.g., gender of a person, and relational context inheres in more entities, e.g., the marriage of Friedrich and Mathilde<sup>2</sup>. Clearly, intrinsic context coincides with *u:quality universal* discussed before. These notions are foundational to a *u:situation* [25]: a particular state of affairs that is

<sup>2</sup> In a happier universe (for Friedrich), when, in 1876, Mathilde would have accepted his proposal.

relevant to applications, constituted by  $u:entity$  and  $u:context$ , together representing the conceptualization of a particular state of affairs: a married couple having an evening walk, the wife showing a 80BPM heart rate. Thus, by aligning concepts around examinations with these concepts around situation, we can provide for situation-aware examinations (usually referred to as context-aware), as depicted in Figure 8.

An examination, as shown in the previous section, requires resource participation of a  $d:examination\ system$  and a  $d:system$ . In the example, a person acts as the latter, whilst a heart rate monitor, in this case a HR wrist watch monitor, acts as the former. As formulated by [23], both are *entities* that bear *intrinsic context*. The *person* bears *gender* and *age*, and the photo detector of the *watch* bears a photoconductive *u:quality* that relates to the underlying *skin color*. The *sensor location* represents *relational context* that inheres in the *watch qua-wearable* and the *wrist qua-wearing-location*. This implies that by bearing intrinsic and relational properties, the  $d:system$  and

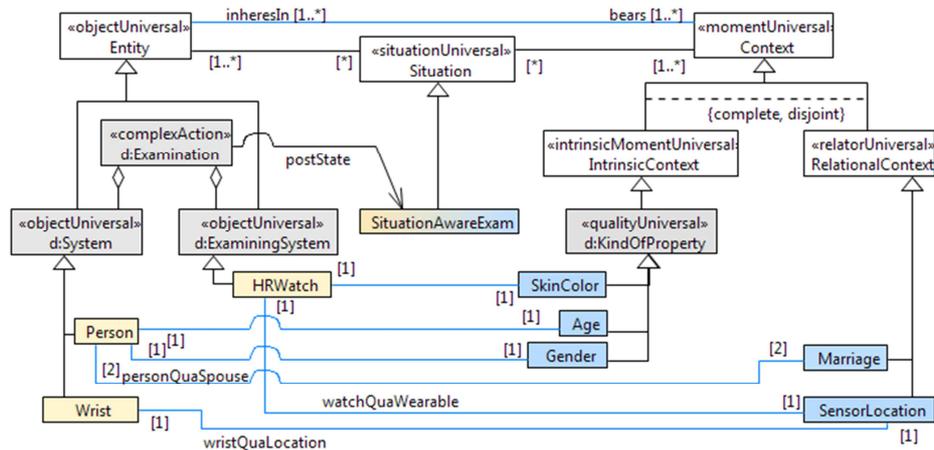


Figure 8 Examination in context, aligned to UFO (white boxes, and profiles). Blue lines indicate  $u:inference$  relations. Blue/yellow boxes indicate examples of contextual/contextualized concepts, respectively, that constitute the situation-aware examination (grey boxes).

$d:examination\ system$  that take part in the  $d:examination$ , bear context that constitutes the *situation* around the  $d:examination$ . This *situation aware examination*, in addition, and by token of the  $d:examination$  being an  $u:action$ , results in a post-state *situation* characterized by the intention to create examination results. Space restrictions prevent elaborating the social aspects of  $d:examinations$  and we refer to [9] for its foundations.

## 5. Concluding remarks

We have shown that sensor data (a) are inconclusive without awareness of the context of the observation, and (b) critically depend on the extent to which sensor data are comparable. We have proposed an ontology, ContoExam, that addresses these issues by provisioning a unifying capability for context-aware expressions of observations about quantities and properties alike. Based on, and scoped by the definitions that have been internationally agreed upon by the discipline of metrology as laid down in the VIM, and their extensions in examinology as laid down in literature, ContoExam adds the capability to reason over the terms that are most prominent in metrology and examinology. We emphasize that we didn't add new or change current metrological or

examinological definitions, as that would be outside the scope of our problem, i.e., to provide for ontological sound reasoning support for the current conventions. As a side-effect, for those terms in the VIM that are aligned by ContoExam to UFO-concepts, those terms will have become ontologically more accurate [26]. We provided for their ontological grounding by aligning these definitions with the Unified Foundational Ontology, UFO, with a small extension towards the application of semantic reference spaces, as presented by [13]. As a result, as opposed to almost all of the current ontologies on sensors and sensor system, ContoExam is not only capable of expressing measurements of quantities but examinations of properties as well. Moreover it provides for an ontologically sound foundation about kinds of properties for reasoning about comparability between obtained measures. Finally, it provides for expressiveness about the context in which these measures were obtained, enriching the definitions of the VIM and its extensions with a situation-aware dimension.

We have experienced that the Unified Foundational Ontology (UFO) provides for a sound and rich foundation that can be successfully applied for turning vocabularies into a proper ontology. ContoExam, as a specialisation of UFO, facilitates a very broad range of applications to uniformly express observed measures. When measures are influenced by the judgment or subjective response of a person, such observations are considered outside the formal definitions of metrology and examinology. We argue that ContoExam, due to its ability to incorporate nominal properties, in combination with its ability to formulate reference spaces on conventional basis only, could also be applied for these more subjective forms of examinations that are of interest to the disciplines of psychology, sociology, biology and alike. This is relevant since for these fields of scientific research, the interest in making observations of humans have shown an increase that is more than twice that of more conventional disciplines that apply examinations, such as physics, chemistry and economics [5].

We have applied a preliminary OWL-version of ContoExam in a mobile platform for body sensors [10], the results of which have been presented in [11] and [12]. In short, their results have shown that the advantage of our approach above conventional approaches is in its flexible behaviour with regards to applied (type of) sensors and varying demands from applications. ContoExam shows to provide for an abstract vehicle about making observations about the reality that can be easily constrained to represent the actual observatory part of the domain's universe of discourse. Although sensors deliver the same bits of data independent of the application domain, ContoExam enables these data to have distinct representations in different applications, concurrently. This provides for true open sensor networks that, subsequently, stimulates innovation and reduces cost of ownership. Future work should address the application of ContoExam in subjective fields of observations. Next, although it represents the core of metrology and examinology, still many parts are left without proper ontological alignment. Finally, a complete OWL-implementation of ContoExam would be an interesting vehicle for the further evolution of the UFO tooling support in application domains that require observations.

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