The semantics of sensor observations based on attention

Simon Scheider*[a,1], Christoph Stasch[a,2]

[a]*Institute for Geoinformatics, University of Münster, Heisenbergstrasse 2, D-48149 Münster*

Abstract

Increasingly large amounts of data are being generated by technical sensors distributed in the human environment. However, a naked sensor value alone is meaningless. It lacks crucial meta-information, including the support and spatio-temporal resolution, and more generally the observation and interpretation process in which it is embedded. In order to make use of the wealth of knowledge underlying sensor data, information science faces the challenge of making this context explicit. In this chapter, we argue that there is a close correspondence between human attention and sensor observation in the sense of a technical metaphor, and that this analogy *serves to explain how humans attribute meaning to technical sensor observations*. The semantics of sensor observations can be described in terms of an attentional process in which a technical observer draws the attention of another observer to something. We argue that this analogy allows to describe the observation context on a very general level and to precisely define terms such as technical observation, time and space of measurement, resolution, in-situ and remote sensing. The suggested vocabulary may be used for sensor and data discovery as well as automated sensor classification.

Keywords: sensor semantics, human attention, sensor observation, resolution

Email addresses: `simon.scheider@uni-muenster.de` (Simon Scheider*), `staschc@uni-muenster.de` (Christoph Stasch)

[1]Research associate, +49 251 83-30088

[2]Research associate, +49 251 83-39760

1. Introduction

How can we know what a sensor is actually sensing? How can we know that a measurement is actually a measurement *of* something? At first sight, answers to such questions seem primarily of philosophical interest. Sensor and measurement technology is based on established scientific practice, and in contrast to philosophers, practitioners do not have to bother about the epistemological basis of their practice provided that it does what it should. At closer inspection, however, these questions reveal a practical problem. Understanding the meaning of a measurement or sensor value allows us to *compare* it in certain specific ways, as well as to *communicate* it, and thus to make use of it in technical applications across particular groups of practice (Probst, 2008).

The value of a measurement is a formal symbol, e.g., a number. Measurement values require a precise interpretation. This includes what we call the *observation context*, such as the *observed feature* (i.e., the object which has the measured quality), the *spatio-temporal resolution* (Degbelo and Kuhn, 2012), the *scale of measurement*, the *observation process*, as well as the *phenomenon* being sensed. As science requires inter-subjectivity, such an interpretation must be *reproducible* (Boumans, 2005). This means that different scientists need to come to equivalent results when interpreting numbers in a standard way.

Over hundreds of years, the sciences have established reliable routines of measurement which allow them to abstract away from its observation context. Tracing the establishment of a technical measurement term which is now taken for granted through the history of science, as was impressively done by Chang (2004) for the notion of temperature, can sometimes reveal surprising complexity. For example, keeping fix points of the temperature scale (e.g. $0\,^{\circ}\mathrm{C}$ and $100\,^{\circ}\mathrm{C}$) fixed puzzled generations of researchers, since boiling points move with the change of environmental and pressure conditions. How can we determine fix points for defining a thermometer without already relying on this thermometer? In a similar way, one can ask what exactly establishes the observation context of a technical sensor without already relying on this sensor. Chang (2004) argued for a strategy of *mutual grounding*, where different sources of experience and measurement are coherently combined.

Science has developed highly sophisticated expert languages. However, the latter *require such routines to be already established*. For example, Newtonian physics requires that the terms space, time and mass are established in terms of measurement routines, in order for terms like mechanics, gravitation and electromagnetism to have any understandable meaning (Lorenzen, 1964). This, however, makes it difficult if not impossible to talk about the basis of measurement and sensing in the language of this science itself (Kamlah and Lorenzen, 1996). It also leads to the problem that scientists have difficulties in saying precisely what these routines consist in, such that people from other disciplines could possibly know what they are talking about. We tend to forget that the foundations of scientific progress are based on culture, not nature (Kamlah and Lorenzen, 1996).

Information science is directly confronted with the consequences of this cultural obliviousness. In the age of the Web, information about measurements and sensors abounds and may offer a new way of doing science (Hey et al., 2009). However, the underlying cultural practices are usually not part of this information. Thus a user of the information is often left alone with the problem of guessing what was meant. In recent years, the problem of describing the semantics of sensors has gained attention (Sheth et al., 2008). It is part of a larger challenge of providing meta-data for scientific data management (Gray et al., 2005). However, as Corcho and García-Castro (2010) argue, it is still unclear how *abstraction and quality levels* of sensors should be described, and this includes, in particular, aspects of their observation context.

In this chapter, we propose to approach this problem from an unusual *human-centric* rather than a *techno-centric* view. This allows to make explicit the underlying cultural techniques. For this purpose, we suggest to regard sensors and measurements as *extensions* of human competences for observing the environment. The latter are based on *human attention*. To illustrate our approach, we use two examples throughout the paper.

Example 1: Temperature measurement. A temperature sensor has been installed, as part of a weather station, on the top of our institute. It follows the general conventions for measuring air temperature. The question is to what exactly the sensor raises attention, and this, in turn, relates to the question why it has been installed on top of our institute and what exactly is represented by a particular data set.

Example 2: Camera observations. Cameras are used to take pictures of remote scenes. They can move their focus and can be moved themselves. Describing the meaning of data produced by cameras, such as remote sensing data, involves understanding not only the light spectrum sensitivity of the camera but also its angle of view in time and space.

In the next section, we discuss background work. In Section 3, we present our main idea and introduce a sensor language which allows to distinguish basic notions of the observation context in terms of attention. In Section 4, we apply our approach to the sensor examples, before we conclude with an outlook in Sections 5 and 6.

2. From sensor technology to culture and back

In this section, we discuss related work on sensor semantics as well as on human attention with the goal of highlighting the cultural roots of technical observation. In doing so, our intention is not to deny or level the fundamental differences which exist between human-level observation and technical sensing, both regarding the (cognitive) sensing processes that are going on, as well as regarding the distinctively intentional behavior of human agents. Rather, we argue that the meaning of technical sensor measurements requires to understand the essential role of the "human in the loop".

2.1. Describing the semantics of sensor observations

Originally, technical sensors were deployed for special application purposes, and those analyzing the data usually had precise knowledge about the sensing procedure and the context in which the observations were taken. With a growing amount of sensor observations available in the Web, the need for standardized meta-data and formalized semantics[3] of sensors and sensor observations became apparent, as the distance between those who collect the data and those who are using the data increases.

The Sensor Web initiative of the Open Geospatial Consortium (Bröring et al., 2011) aimed to address this issue by introducing a standard for the description of sensors, the Sensor Model Language (Botts and Robin, 2007) as well as the Observations & Measurements standard[4] (International Standardization Organisation (ISO), 2011). However, these standards largely address interoperability of sensor observations on a syntactical level. The *semantics of observation data* and especially the observation context of sensors are not well captured (Probst, 2008).

The NASA SWEET ontologies[5] are basically taxonomies of observable phenomena. The relation of sensing devices to observable properties and observations is not captured therein.

[3]Note that the term "semantics" is not restricted here to the meaning of a linguistic utterance, but rather involves *structured formal data* among the symbols whose meaning is in question. Thus the term is used as in Information Ontology and Information Science.

[4]The Observations & Measurements standard has also been published as an ISO standard.

[5]The SWEET ontologies are accessible at `http://sweet.jpl.nasa.gov/ontology/`.

The World Wide Web consortium initiated an incubator group for semantic sensor networks (SSN)[6] in order to develop ontologies for describing the capabilities of sensors and related observations. The group proposed the SSN ontology (Compton et al., 2012), which allows to link sensing procedures, their implementation in terms of sensing devices, and the observations generated by sensors. The ontology allows to capture some of the observation context and comes closest to our approach.

However, there are some general problems with these approaches. All of them describe the "carriers" of observed qualities in terms of so called "features of interest", i.e., objects whose qualities are being sensed. However, it is often unclear whether there is any corresponding object involved in a measurement. For example, think about the measurement of air temperature. There seems to be only a quality involved without any identifiable object. Furthermore, the approaches leave open what the spatial and temporal support is and how the spatio-temporal resolution of a measurement was generated. Support and resolution may not be associated with any object. We argue that this can be made explicit if we take into account the attentional focus as a carrier of information and as a spatio-temporal referent[7]. Current approaches also seem to conceive of the sensing process as a kind of simplistic unidirectional information flow from the environment (stimulus) to a device, rather than a result of complex human-technological interaction. As a particular consequence of this view, the approaches fail to capture intention ("Why is the sensor deployed at this location with this particular sampling rate?").

2.2. The cultural relevance of (joint) attention

Attention is the human capacity of bringing a certain aspect in the window of perception to consciousness. In order to understand the cultural relevance of this mechanism, one first has to understand what we mean by *window of perception* and by *bringing to consciousness*.

Recent cognitive research has widely converged to the view that perception is *unconscious* or *pre-conscious* to a large extent (Pylyshyn, 2007). This means that perceived phenomena as well as the embedding in their surroundings, e.g., moving objects in a visual field, are not a product of an abstraction from neutral sensor signals that humans are aware of, but rather a product of subconscious routines

[6] `http://www.w3.org/2005/Incubator/ssn/`

[7] In addition to providing carriers of information, attention is also active in constructing information, due to its selective and reflexive character, compare Glasersfeld (1995). We focus in this chapter on the former aspect.

which *autonomously project* those phenomena into a signal background (Scholl, 2001). Through this very process (the precise working of which is still largely unknown), our perceived world, as a matter of fact, is not one of disturbingly neutral pixels or sensor signals, but one of *intuitively graspable phenomena* coming with *a multitude of stable perspectives* (Lehar, 2003).

In such a perspective, phenomena are circumscribed with respect to a background, in pretty much the same manner as Gestalt psychologists envisioned *figures* to be identified with respect to a *ground* (Köhler, 1992). We call background and foreground the window of perception. By moving the scope of our visual field, we move the ground, and with it, different figures are being reified subconsciously in the foreground.

Human attention allows to select from this window of perception in order to bring certain aspects to mind, just like an index (Pylyshyn, 2007). We can consciously *focus our attention* on either some of these phenomena[8], or to the background, or to arbitrary parts thereof, without spending any effort on consciously encoding sensoric properties. However, our attention is finite, and thus attentional foci are finite, too (VanRullen and Koch, 2003). Infinite space, in contrast, is an abstraction which may be based on our experience of repeatability of attentional focusing (Scheider and Kuhn, 2011).

The cultural relevance of this attentional mechanism is substantial. In a nutshell, it explains why humans can have different *perspectives* on a domain while at the same time being able to *share* them. It is this capacity for sharing perspectives by guiding human attention which enables humans to develop a natural language, and to play an active role in the establishment of its semantics.

Many authors have argued for basing human concepts and language on attentional perspective. According to linguists like Langacker (1987) and Talmy (2000), the mechanisms of scoping, scanning and focusing attention are basic for the semantics of nouns and verbs. Langacker (2005) suggested attentional behavior as basis for logic as well as linguistic meaning. Glasersfeld (1995, 1981) suggested reflexive human attentional behavior as a basic tool of conceptual construction. Carstensen (2007) based top-level ontological distinctions on attention. Marchetti (2006) proposed the research field of attentional semantics, which identifies human attention as the center point of semantics research.

Other authors have argued that attention is responsible not only for generat-

[8] Some scholars think we can pay simultaneous attention to at most 4 phenomena (Pylyshyn, 2007).

ing perspective, but also for sharing it, and thus for rendering meanings intersubjective[9]. The anthropologist Michael Tomasello explains how humans are able to exchange perspectives and language across individuals and generations (Tomasello, 1999). It is the process of *joint attention* which allows humans to effectively guide each other's attention.

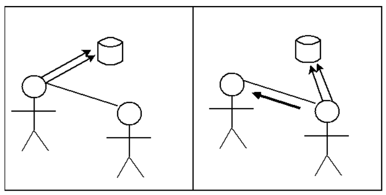


Figure 1: Two types of intentional interaction: following someone's attention to something (left, thin arrows) and drawing someone's attention (right, thick arrow) to something, cf. Tomasello (1999).

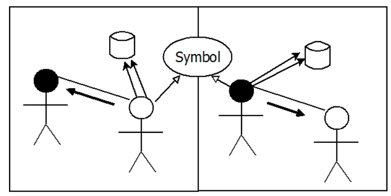


Figure 2: A speech act (symbol uttering) is a special case of drawing the attention to something, cf. Tomasello (1999).

Humans join their attention if they *mutually draw each other's attention to something in their perceptual window*. Drawing the attention is an atomic form of a *speech act*. It makes others aware of something in their perceptual window by overtly focusing on it or pointing to it. This requires interaction in a triadic manner (compare Figure 1). Two agents, one in the role of a *guide*, the other in the role of a *follower*, need to interact with each other and with some phenomenon in this way:

1. The guide needs to *focus on a phenomenon* and thereby *prompts a following*
2. The follower needs to *perceive the guide focusing* on something, and to understand this as a *prompt* to follow the guide's attention
3. The follower needs to *follow the attention* of the guide with his own attention (based on visual or other clues).

According to Tomasello (1999), if the two agents exchange roles in this interaction game, then they make each aware of the other's intentions towards the world. There is a considerable complexity hiding behind joint attention, as it requires not only attention perception and manipulation, but also *social coordination* (because of the exchange of roles) and *intentional understanding* (Kaplan and Hafner,

[9]For a discussion of how this contributes to solving the problem of semantic reference, see Scheider (2012).

2004). The latter is needed because the perceived attentional act of the guide is understood by the follower as having the intention to guide his own attention, which, by recursion and through role exchange, leads to an arbitrarily complex chain of mutual awareness (Peacocke, 2005).

What is of interest here is how drawing attention supplies a basic pattern of a speech act which allows to establish meanings and referents of symbols (Figure 2). We argue that it is exactly this pattern which allows humans not only to impute meanings to other observers, but, in a metaphorical sense, also to technical sensors.

2.3. Sensors as artificial limbs for human attention

Let us think for a moment about what technical devices exactly are. Technical devices allow *humans to do things they are not able to do without them*. That is, they increase the efficiency and range of human action. Think about Galilei's telescope, which allowed him to distinguish the rings of Saturn (Eco, 2000), the microscope, which allows humans to see things that are too small to see for the human eye, or Wedgewood's pyrometer, which allowed for the first time to measure temperatures such as the melting point of iron (Chang, 2004). Technical devices are like artificial human limbs, as Eco (2000) argued. They extend the range of human action into unknown territory. This implies, however, that technical devices can be properly understood only in the context of human action. This insight sounds obvious, however, it has some not so obvious consequences.

The question arises what kinds of human action are extended by technical sensors. We suggest that humans *extend the range of their attention* by using sensors which *reliably draw their attention* to something which is not directly perceivable. This is the case for the image of the Saturn on the lens of Galilei's telescope (Eco, 2000), or the contraction of the pieces of clay after cooling in Wedgewood's pyrometer (Chang, 2004), which allows measuring the temperature they were exposed to. The lens image and the clay contraction have a meaning only because they reflect something else, namely the Saturn or high temperature. In this, they are similar to *indexical signs*. However, they are special, since they stand for something which itself could not be a subject of perception of a human observer. At Galileo's time (1610), the rings of the Saturn were too remote to be observable. And very high or very low temperatures cannot directly be experienced by a human being. Which means, they are to some extent "invented" by humans (Chang, 2004).

Modern technical sensors encode their measurement results into symbols, which are automatically fed into the Sensor Web. We argue that also in this case, symbols get their meanings through extending human attention. This process may consist of various attentional processes and may involve several people, as we will see. In the following, we will analyze this process in detail and describe it in a formal model.

3. The technical extension of human attention by sensors

In this section, we will give the idea which was motivated in the last section a precise form. This allows us to specify the meaning of some central terms of the sensor observation context.

3.1. A sensor language based on attention

The formalism is written, implemented and tested in *Isabelle/HOL*, a typed higher-order logic (HOL) which allows for reasoning over functions. We adopted the notational style of Isabelle, since it follows ordinary conventions known from logic and mathematics books, and thus should be readable. Furthermore, we also tested and proved all our theorems with Isabelle[10].

A theory in Isabelle consists of (1) declarations of *(basic) types* and *type definitions*, using type constructors such as $'a \Rightarrow 'b$ for function types and $'a$ *set* for the type of sets with elements of type $'a$, with variables $'a, 'b, 'c$ standing for some types. We also use *sum types* $'a + 'b$, i.e., types that are the union of two other types. Sum types allow us to express a kind of type hierarchy[11]. In this paper, types are written in uppercase letters. Theories furthermore consist of declarations of (2) *constants*, which include *functions* and *object constants* in lowercase. Declaring constant c or variable v to be of a certain type T is done using double colons, e.g. $(v :: T)$ or $(c :: T)$. *Predicates* are just functions that map into the predefined type *bool*, e.g., $(p :: T \Rightarrow bool)$. Isabelle theories furthermore may contain (3) *non-recursive definitions*, which are introduced in this paper by the numbered **Definition** environment with the symbol ==, as well as (4) *axioms* as arbitrary sentences in HOL. For the latter we use the numbered **Axiom** environment.

$f\ a$ means applying function f to a. $\iota x.P\ x$ denotes the unique x that satisfies the predicate P. Functions are always *curried*, i.e., function domains are written as a (right-associative) concatenation of functional types:

---

[10] `http://www.geographicknowledge.de/vocab/attentionalmodel.thy`.

[11] In order to simplify our syntax, we do not use any “upcasting” or “downcasting” sign for sum types.

$(((f ::' a \Rightarrow' b \Rightarrow' c)(a ::' a) ::' b \Rightarrow' c)(b ::' b) ::' c)$. Furthermore, in Isabelle, all functions are required to be *total*. Logical symbols are used in a common way.

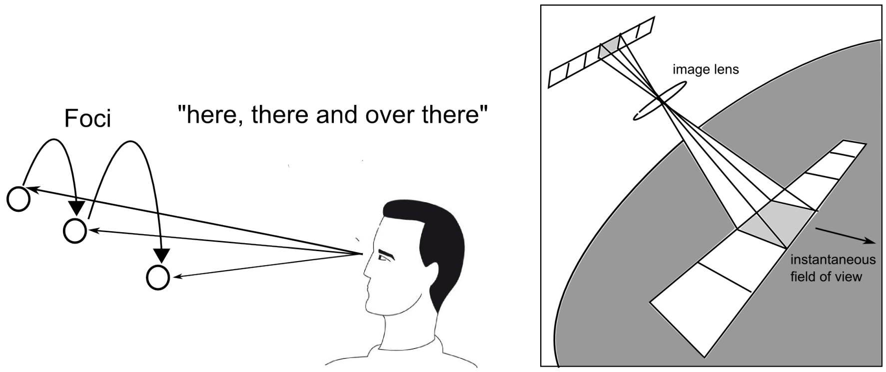
3.1.1. Attentional focus and agent

In a first step, we introduce the notion of a *focus*. In a standard sense, a focus is an entity which is generated by some human agent focusing his or her attention on something (compare Figure 3a). Humans move their attention, e.g., in correspondence with their saccadic eye movements to objects in their visual field, which generates granular entities which enter their consciousness (Pylyshyn, 2007). Humans can focus on their perceptual window as well as on abstract entities, such as the number 3 (not the symbol, but the mathematical entity). Following Langacker (2005), abstract entities are assumed to be located inside an *imaginary window*. Inside the perceptual window, one may focus either on some *phenomenon*, e.g., some perceivable object or event, or on some arbitrary spot which lies, e.g., halfway in space between two objects (Scholl, 2001).

In a non-standard sense, however, a focus may also be interpreted as the focus of a sensor. This correspondence is illustrated by Figure 3b in terms of the so called *instantaneous field of view* (IFoV) of a remote sensor (satellite). The IFoV corresponds to the spatio-temporal focus of a single pixel in a satellite image, i.e., to some area on the ground and some time interval during which the sensor recorded surface radiation. In this case, we use the idea of an attentional focus *as a metaphor* (Lakoff, 1990). This means that we behave for a moment *as if* the act of attentional focusing could be played not only by a human being, but also by some technical sensor.

One may legitimately ask whether we confuse two incomparable processes here. As a matter of fact, human agents are not sensors. As argued above, attention is intentional behavior, directed towards objects which are subconsciously circumscribed against some perceptual background. Technical sensing, in contrast, is based on a simple stimulus response mechanism on signals. That is, our metaphor should not be mistaken as identity of the underlying process categories.

In order to understand what is going on here, we need to understand first how attention can be *metaphorically imputed* (by humans) to technical devices instead of humans. This imputation does not entail that process categories are identical, but rather that an observer is able to disregard the differences in favor of a certain view which helps handle and understand measurements.



(a) Foci of attention of some human observer.

(b) Instantaneous field of view of remote sensor.

Figure 3: A *focus* is an abstraction over foci of human attention and spatio-temporal sensor foci. In both cases, foci are results of a shifting observation process, which takes into focus a given excerpt of the environment at a given moment.

3.1.2. Signs and triadic attention

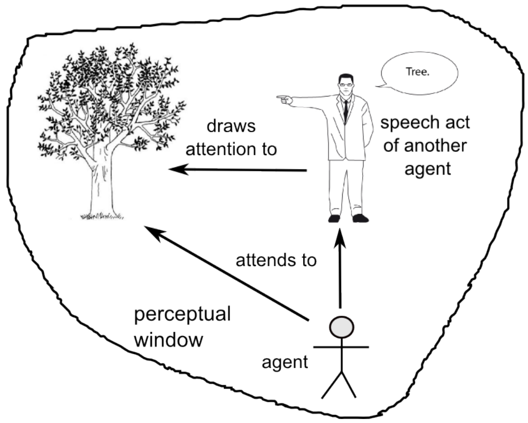
For this purpose, we make precise the idea of a *sign* in terms of attention. In this paper, signs are perceivable phenomena which are capable of *drawing the attention* to some other thing[12]. As illustrated in Figure 4, this idea of a sign applies to a variety of phenomena, ranging from *pointings*, which are *speech acts* in a narrow sense of the word, to *formal symbols*[13].

In all these cases, we have an agent (the "follower") whose attention is drawn by the sign to something else, either based on conventional training in the case of a formal symbol, or by attentional following in the case of a perceived pointing. That is, we have a triadic relation between a *sign*, something to which it draws attention, and a follower who attends to both (Figure 4).

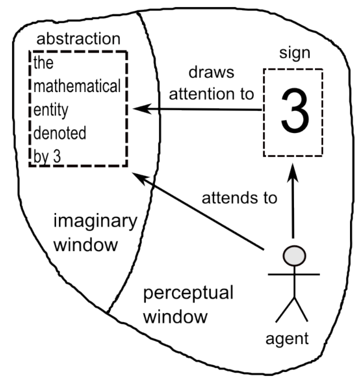
From the perspective of the follower (who is also an observer), the sign, i.e., the speech act or symbol, as well as the thing to which attention is drawn, are contained in his or her perceptual or imaginary window. That is, in any case, *it is*

[12]The referent of the sign. In distinction from objectivist philosophy, we do not hold that signs refer to or denote referents *by themselves*. Symbols do not mean, only people do. But they do it indirectly, via drawing attention based on symbols.

[13]Peirce and many researchers in semiotics distinguished *symbols* (as formal signs), *icons* (which resemble what they stand for) and *indexicals* (which are similar to pointings) (Eco, 1977). We will not emphasize these distinctions here, and they are all compatible with our notion of a sign.



(a) A speech act draws human attention to something else, e.g., to something in focus in the perceptual window.



(b) Signs are capable of drawing human attention also to foci in an imaginary window.

Figure 4: The correspondence of speech acts, such as pointings (German: Zeigen), and signs (German: Zeichen).

a human observer who imputes the roles of the attentional triangle to perceived or imagined entities. This corresponds to Peirce's dictum: "Nothing is a sign unless it is interpreted as a sign".

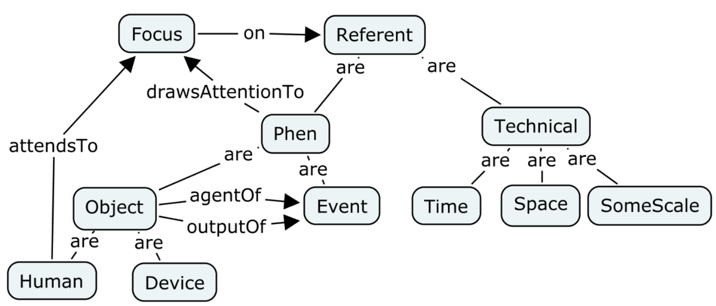


Figure 5: Basic attentional model as RDF theory. Arrows indicate domain and range restrictions on relations. The relation "are" links subclasses.

In order to formalize this basic idea, we make use of three formal types, namely *foci*, *phenomena* and *referents*, as introduced in Table 1 and Figure 5. Corresponding to the "follower" agent discussed above, we assume that there is an

Table 1: Some formal types of an attentional theory of signs.

Type	**Description**	**Examples**	**Isabelle declaration**
Focus	foci of attention of an observer	here (now), there (then), ...	*start* | *moveFocus Focus*
Phen	phenomenon in the perceptual window of an observer	perceivable objects (humans, devices) and events	undefined
Referent	type of things on which one can focus attention.	supertype of phenomena and technical referents. In contrast to perceivable phenomena, technical referents are abstractions, such as the temperature denoted by 15 °C	*Phen* + *Technical*
Technical	technical referent.	see below	*Time* + *Location* + ...
Time	temporal referent.	xsd:datetime, e.g., 2001-10-26T21:32:52	*rat set*
Location	spatial referent.	WGS84, e.g. 52° North, 7° East	($rat \times rat$) *set*

(implicit) human observer who moves his attentional focus[14] on phenomena in his or her perceptual window as well as on technical abstractions in some imaginary window. Phenomena may be other human beings, technical devices, symbols as well as events. Technical abstractions may be the temperature denoted by 15 °C. Both remain undefined in our formalism[15].

Both abstractions and phenomena are also called referents, since they can be referred to by agents through focusing attention on them. We distinguish several *kinds of phenomena* on which one can focus, such as humans, devices, objects and events. An overview of all these concepts together with their relations is given in Figure 5. The figure is based on a simplified RDF[16] version of our theory.

[14]This movement may be defined by a recursive type declaration, which constrains foci to be only those entities generatable by some recursive function *moveFocus*, which stands for the shifting of attention of the implicit observer.

[15]This acknowledges the fact that both Gestalt perception as well as technical referents are not reducible to a logical definition. For example, even though we may consider temporal referents in terms of rational numbers, these numbers involve a unit of measure (e.g. an hour) which is not logically definable.

[16]Resource description framework, see `http://www.w3.org/RDF/`. Subclass hierarchies are easier to handle in RDF than in Isabelle, while Isabelle allows more expressive definitions. In this

We introduce now a small set of relations on instances of these types (Table 2), which a human can distinguish. The function *on* returns for each focus some referent on which it is focused. We use a function because we assume there is always a unique thing of that kind[17]. We can now distinguish those foci of attention which are on perceptual phenomena (i.e., which focus on the perceptual window) from those focused on abstractions (i.e., which are inside some imaginary window):

Definition 1 (Perceptual). $(\mathit{Perceptual} :: \mathit{Focus} \Rightarrow \mathit{bool})\, f ==$
$(\exists (y :: \mathit{Phen}).\mathit{on}\, f = y)$

The implicit human observer can also identify participants in an event. We distinguish two types of participants, namely the *agentOf* some event, and the *outputOf* some event. Agents are objects which play some active role in the event, while outputs are objects which are generated by the event.

attendsTo is a central relation in the sign triangle. It expresses that some object (in the perceptual window of the implicit observer), such as another human being, apparently *pays attention to some focus*. Note that this focus was actually generated by the implicit observer of the scene, not by the perceived object. However, *attendsTo* expresses that the implicit observer followed the attention of the object (e.g., the human gaze) and took the focus as that which the object apparently focused on. That is, *attendsTo* expresses an implicit *attentional following* of the observer, as described in the triangle of Figure 4a.

The most essential relation of this triangle is a function which is called *drawsAttentionTo*. It expresses that some sign draws attention to some focus (such that observers *are intended* to follow with their attention). The sign may be any kind of phenomenon, e.g., an object or an event. We use this relation to formally define signs below.

We add some axioms which describe these relations in more detail. For example, only objects can attend to something[18]. Agents are objects which participate in events. Outputs are also objects. Furthermore, agents can draw attention to some focus only once, i.e., through a unique event. That is, there can be at most

---

paper, we treat phenomenon superclasses as Isabelle types and phenomenon subclasses in terms of predicates. Thus our class hierarchy is not fully reflected in terms of Isabelle types.

[17]Note that there may still be several foci at a time. Foci are like “fingers on instantiations” (Pylyshyn, 2007).

[18]In a less metaphorical setting, one could require that only humans can attend to something. However, we would like to impute attention to devices and thus need to leave this possibility open.

Table 2: Relations between things in an attentional sign triangle

Declaration	Description
$on :: Focus \Rightarrow Referent$	Returns the referent on which a focus is "focused"
$attendsTo :: Phen \Rightarrow Focus \Rightarrow bool$	Phenomenon attends to some focus
$drawsAttentionTo :: Phen \Rightarrow Focus$	Returns the focus to which some phenomenon draws attention
$agentOf :: Phen \Rightarrow Phen \Rightarrow bool$	Phenomenon is an agent of some event
$outputOf :: Phen \Rightarrow Phen$	Returns the output of some event

one drawing of attention of a certain agent to a certain focus. This assures that an observation of an agent is unique in space and time.

Axiom 1 (Attentional drawings). $attendsTo\ a\ b \rightarrow Object\ a$
$agentOf\ ag\ e \rightarrow Event\ e \wedge Object\ ag$
$outputOf\ e = o \rightarrow Object\ o$
$(drawsAttentionTo\ e = drawsAttentionTo\ e') \wedge agentOf\ a\ e \wedge agentOf\ a\ e' \rightarrow e = e'$

Based on these primitive concepts, we can supply a definition of a sign. Remember that functions in Isabelle are total. Since *drawsAttentionTo* is a function, all phenomena draw the attention to something, whatsoever. How can we then distinguish signs from arbitrary phenomena? Simply by conceiving phenomena which are not signs as things which draw the attention (only) to themselves. Signs can then be defined as exactly those phenomena which *draw attention to something else* (i.e., as phenomena which are not self-referential):

Definition 2 (Sign). $(Sign :: Phen \Rightarrow bool)\ s\ \ ==\ \ on\ (drawsAttentionTo\ s)\ \neq s$

We can go on now and define different kinds of signs, depending on what kinds of objects and events are involved in the attentional drawing. For example, one may define a speech act as an event sign (a sign which is a perceived action), and a speaker as a required agent of this event. We may define a symbol, in slight deviation from its usage in semiotics, as an object sign (a sign which is an object). Furthermore, we can define speech as a speech act with some output, and restrict this output to be a symbol, i.e., an object which is a sign itself.

Definition 3 (Speech and Symbol). $(SpeechAct :: Phen \Rightarrow bool)\ e ==$
$Sign\ e \wedge Event\ e$
$(Speaker :: Phen \Rightarrow bool)\ a == (\exists e.agentOf\ a\ e \wedge SpeechAct\ e)$

$(Symbol :: Phen \Rightarrow bool)\ e == Sign\ e \wedge Object\ e$
$(Speech :: Phen \Rightarrow bool)\ e == SpeechAct\ e \wedge (\exists a.outputOf\ \ e = a)$

Axiom 2. $SpeechAct\ e \rightarrow (\exists a.agentOf\ \ a\ e)$
$SpeechAct\ e \wedge outputOf\ \ e = s \rightarrow Symbol\ s$

3.1.3. Observations

What does it mean that someone observes something? We suggest that observation is more complex than perception in that it requires also a communicative act. However, it is not simply a drawing of attention to a certain spot in the environment. It also results in a report about *what* was observed, i.e., a symbol which itself draws attention to the observed referent. As depicted in Figure 4a, because of the triangular relation of signs, this implies that besides the implicit observer, there must be a perceived observer who draws attention to some spot in the perceptual window and at the same time utters a description which refers to some referent. In essence, observations are therefore utterances of symbols which are at the same time pointings to some perceptual focus:

Definition 4 (Observation). $drawing\ e\, f\ ag ==$
$(drawsAttentionTo\ e = f \wedge agentOf\ ag\ e)$
$obsdrawing\ e\, f\ ag\ r == (drawing\ e\, f\ ag\ \ \wedge Perceptual\, f\ \wedge$
$on(drawsAttentionTo(outputOfe)) = r \wedge r \neq (outputOfe))$
$observes\ ag\ r\, f\ == \exists\ e.obsdrawing\ e\, f\ ag\ r$
$Observer\ ag == \exists\, f\ r.observes\ ag\ r\, f$
$Observation\ e == \exists\, f\ ag\ r.obsdrawing\ e\, f\ ag\ r$

In this definition, $drawing\ e\, f\ ag$ means that e is a “drawing”, i.e., an event by which some agent ag draws attention to some focus f. An observation is a special kind of drawing which additionally refers to some (potentially abstract) referent r observed at some perceptual f by way of some symbol output. $observes\ ag\ r\, f$ means that the agent ag observes referent r at focus f. Due to Definition 4, this simply means that there is a drawing to some perceptual f (*obsdrawing*) which at the same time generates some output which itself draws attention to some referent r (compare Figure 6). The agent is also called *observer* and the event is called *observation*[19]. The two implicit observers in Figure reffig:att4 are not part of the

[19]Note that the picture of the pointing man stands for an event, namely the pointing, not for the involved agent.

formalism and they may actually be the same person. The referent r needs to be different from the observation output, in order to prevent the production of symbols without meaning.

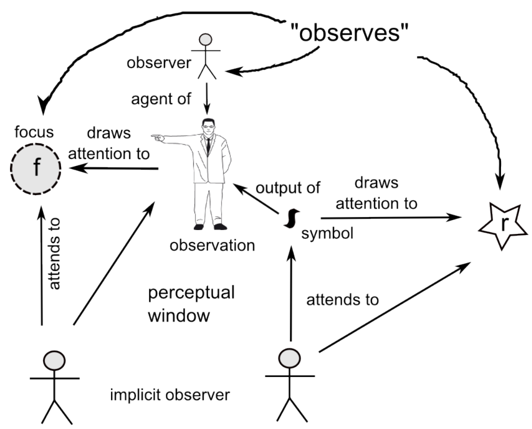


Figure 6: How observers "draw attention" in the course of an observation. An observation is an event (the pointing action) in which the observer participates, and which outputs a symbol.

It can be proved now that if someone observes something, then there is always an observation event involved, as well as some symbol generated by that event:

Theorem 1. $\textit{observes ag r f} \rightarrow (\exists e.\textit{Observation } e) \wedge (\exists s.\textit{Symbol } s)$

Note that the observation event, in being a "drawing", may or may not draw attention to some other thing. In the former case, the event is a speech act, and thus we have actually two triadic sign relations involved, one for the symbol, and one for the speech act which draws attention to some spot, as depicted in Figure 6. The reason why we do not require this is that we would like to leave open the possibility of *self-referential observations*, i.e., observations of the observation itself (compare next section).

Furthermore, based on Axiom 1, it can be proved that an observer can observe at most a single referent at some given focus of attention:

Theorem 2. $\textit{observes ag r f} \wedge \textit{observes ag } r' f \rightarrow r = r'$

This allows to uniquely identify the outcome of some observation, and thus to construct observation functions.

3.1.4. Technical observation

Based on this formal apparatus, we can describe how humans extend their attention in the case of a technical measurement.

We know that a basic semantic capacity of humans is to apply roles to things for which they were not intended, in the sense of a metaphor (Lakoff, 1990). The double triangle of drawing attention, as specified above in our definition of what constitutes an observation (see also Figure 6), serves as an image schema (Johnson, 1987) which can be applied beyond its original realm. We simply assume that the implicit human observer applies corresponding observation roles to a sensing event instead of a human speech act. That is, even though a technical sensor in fact never intentionally *prompts* an attentional following, the implicit observer can act *as if* this was the case, regardless of whether the technical sensor actually has the capacity to do so. The usage of the word "observation" also for sensors in ordinary speech demonstrates that this metaphor is actually in common use.

The metaphor of attentional drawing of technical sensors is depicted in Figure 7. As in the case of a human observation, there are *two different drawings* involved. One is the *drawing of sensing results* (symbols) to some region on a measurement scale. Measurement scales are *abstractions* over experiential values of some phenomena, such as temperature. The other one is the *drawing of the sensing process itself* to its technical focus. While the former drawing is conventional, the latter drawing is based on visual cues of the sensing device and knowledge about the way it was constructed.

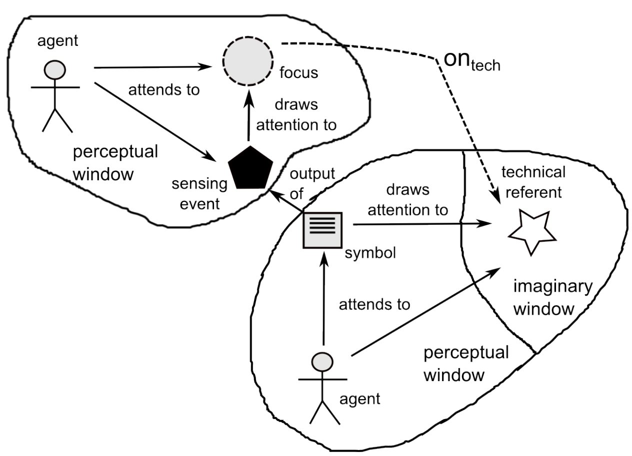


Figure 7: How sensors "draw attention" in the course of a technical observation. We propose that this double triangle also enables the metaphorical extension of human attention by sensors. We denote this by the relation on_{tech}.

We define a measurement as an observation (as defined above) performed by some technical device which outputs some technical referent[20]:

Definition 5 (Measurement). $measure\ d\, f\ r ==$
$observes\ d\ (r :: Technical)\, f \wedge Device\ d$
$Measurement\ e == \exists f\ d\ r.obsdrawing\ e\, f\ d\ (r :: Technical) \wedge Device\ d$

$measure\ d\, f\ r$ means that device d measured technical referent r at focus f. Measurements are the corresponding events.

We can also define a sensor, correspondingly, as an observer which is a device:

Definition 6 (Sensor). $Sensor\ a == (Observer\ a \wedge Device\ a)$

The definition of a measurement introduced above is dependent on a particular device. However, the usefulness of technical observation is based on its independence from particular measurement devices. This independence is a result of *calibrating* instruments with each other, which enables to regenerate equivalent measures across them. We can say that two devices are calibrated if they behave correspondingly on the (non-empty) subset of foci on which measures are taken[21]:

Definition 7 (Calibration). $(calibrated :: Phen \Rightarrow Phen \Rightarrow bool)\ d\ d' ==$
$(\forall\ r\ r'\ f.measure\ r\, f\ d \wedge measure\ r'\ f\ d' \rightarrow r = r')$
$\wedge(\exists\ r\ r'\ f.measure\ r\, f\ d \wedge measure\ r'\ f\ d')$

Calibration introduces equivalence classes of instruments. We can therefore define a device-independent measure by the following relation, where δ stands for any member of such an equivalence class:

Definition 8 (General measure). $genmeasure\ \delta\, f\ r ==$
$(\exists\ d.measure\ d\, f\ r \wedge calibrated\ d\ \delta)$

$genmeasure\ \delta\, f\ r$ means that referent r has been measured at focus f by some instrument calibrated with δ.

[20] The definition actually requires the casting of type *Referent* to *Technical* in Isabelle. This is left out for reasons of better readability.

[21] This is a simplified account. More sophisticated accounts would need to include a certain range of attentional overlap and some kind of theoretical correspondence between measured reference systems, compare Chapter 3 in Chang (2004).

3.1.5. Extending human attention by technical observation

We have suggested above that technical observation involves more than just the production of measurement symbols by some device. It also involves two triadic sign relations, one relating the sensor focus with the measurement event, the other one relating the symbol output with its referent. How does this relation *serve to extend the attention* of an implicit observer?

The problem is that the referent measured by the device is an abstraction and thus cannot be in the perceptual window of the implicit observer. The focus of measurement can only be on perceptual phenomena. However, the observer behaves *as if* the perceptual focus was on the abstract referent.

In terms of our theory, we may say that the implicit observer constructs a new kind of technical *on* relation, which we call on_{tech}. Just as the *on* function, it returns the referent on which a focus is "focused". However, unlike *on*, it always points to a technical referent instead of a perceptual phenomenon. It is defined as the technical referent of some measurement focused on f using some device d, for example some calibrated thermometer *thermo*:

Definition 9 (attention extension). $on_{tech}\; d\, f == (\iota\, r.genmeasure\; d\, f\; r)$
$on_{thermo}\, f == on_{tech}\; thermo\, f$

3.2. The sensor observation context

The apparatus introduced so far can be used to precisely define some basic notions of the observation context, namely time and location of measurement, resolution, as well as in-situ and remote sensors.

3.2.1. Time and location of measurement

Foci of attention can be regarded as a basis for referring to measurable space as well as time[22]. As Marchetti (2009) argues, they provide a non-circular account of time, because experiences of *succession* and *duration* are not attributed to some unobservable physical flow of time, but regarded as results of attentional activity.

The absolute time underlying *temporal reference systems*, such as calendars and standard time, are results of *paying attention to standard periodic artificial or natural events and calibrating instruments based on them*. For example, the ticking of a clock can be used to infer times on foci of attention, based on paying attention to the number of ticks or hourly strikes.

[22]For an approach which demonstrates how spatial reference systems could be logically constructed based on attention, see Scheider and Kuhn (2011).

Let us assume we conventionally establish a certain standard clock, simply called *clock*. Then each and every clock calibrated with the latter will generate "our" specific time. Abstracting from particular instruments, we can define our time as a function *when* from foci into temporal referents based on any clock calibrated by our *clock* standard:

Definition 10 (Time). $(when :: Focus \Rightarrow Time)\, f ==$
$(\iota\, (t :: Time).genmeasure\ clock\, f\ t)$

If we expand on this definition, then $when\, f = t$ holds precisely because there is an (implicit) *ticking event* (i.e., the "observation" event required by Theorem 1) of *some (implicit) clock* (the sensor), which is calibrated with the standard *clock*. This event draws attention to f, which can in this case be considered on the ticking event itself (thus, the event is self-referential, as discussed in Section 3.1.3). The event has, furthermore, generated some symbol (such as "14:00") (according to Theorem 1) which draws attention to some temporal referent t.

If we measure a location by some device, such as a GPS receiver[23], then we proceed analogously. The device triggers an observation event (a so called "fix"), which draws attention to itself (i.e., it is self-referential), just as in the case of a clock. Simultaneously, the device outputs a coordinate, which corresponds to the point location of the fix event and is in some abstract spatial reference system, such as WGS84. Note that the location measured is the one of the fix event, not the device, since the GPS receiver may move (and thus change its location). GPS receivers also need to be calibrated against some standard *gps* in order to be useful.

Definition 11 (Location). $(where :: Focus \Rightarrow Location)\, f ==$
$(\iota\, (t :: Location).genmeasure\ gps\, f\ t)$

If we measure the time and location of a measurement (or observation), then we simply perform two further measurements which measure this event. Simply put, each focus on this event tells us something about when and where the measurement event happens:

Definition 12 (Time and location of observation). $timeofobs\ e\ t ==$
$\exists f.on\, f = e \wedge when\, f = t$
$locofobs\ e\ s == \exists f.on\, f = e \wedge where\, f = s$

[23] http://en.wikipedia.org/wiki/Global_Positioning_System

Note that the location of some object may require a different and slightly more involved observation process compared to the when and where of some focus. In particular, we expect that the location of some object and the location of some focus on the object are spatially related but different.

3.2.2. Spatio-temporal resolution

We are now able to differentiate among the *time and location of some measurement* and the *time and location of the focus of measurement*. The latter may be considered a proxy measure of the *resolution of data* produced by the sensor [24].

The (spatio-temporal) resolution of a symbol *sy* may therefore be defined as the time *t* or location *s* of the focus to which the measurement event, which generated the symbol, draws our attention.

Definition 13 (Resolution). $Resolution_{temp}\ sy\ t ==$
$\exists\ e\ f\ d\ r.outputOf\ e = sy \wedge obsdrawing\ e\ f\ d\ r \wedge when\ f = t$
$Resolution_{loc}\ sy\ s ==$
$\exists\ e\ f\ d\ r.outputOf\ e = sy \wedge obsdrawing\ e\ f\ d\ r \wedge where\ f = s$

Note that both, resolution and location of measurement, imply multiple events and devices, and, thus, also multiple corresponding attentional double triangles. In the case of resolution, these double triangles are linked via the focus of measurement, whereas in the other case, they are linked via the measurement event.

3.2.3. In-situ and remote sensors

Depending on the location of the measurement event which generates a symbol, compared to location of its technical focus, we can distinguish in-situ and remote sensors.

In a nutshell, in-situ sensing happens inside the location of the focus to which the event draws our attention. Remote sensing happens outside of this location, where insideness may be defined simply in terms of subsets of spatial coordinates:

Definition 14 (In-situ and remote sensing). $InSituSensor\ d == Sensor\ d \wedge$
$\forall\ e.agentOf\ d\ e \rightarrow (\forall\ s\ s'.locofobs\ e\ s \wedge Resolution_{loc}(outputOf\ e)\ s' \rightarrow s \subseteq s')$
$RemoteSensor\ d == Sensor\ d \wedge$
$\forall\ e.agentOf\ d\ e \rightarrow (\forall\ s\ s'.locofobs\ e\ s \wedge Resolution_{loc}(outputOf\ e)\ s' \rightarrow \neg(s \subseteq s'))$

[24] The terms *support* or *grain* may also be used as synonyms for resolution as described by Degbelo and Kuhn (2012).

4. The attention analogy by sensor examples

We will illustrate all formal distinctions introduced above by two examples and show how the observation context can be inferred based on our definitions.

4.1. Cameras and satellites

Analog cameras are devices which “observe” a visual layout by way of light exposure events. Each exposure event is a measurement in our sense (since it draws attention to some illuminated layout and outputs a photo, which is a symbol in our sense), and it has a time as well as a location. The time is the time of exposure with light, and the location of the event is the location of the lens inside the camera. Modern cameras therefore have clocks as well as built in GPS devices. But cameras also have a focus, which corresponds to the spatial area taken into focus and is located beyond the lens. This focus is reconstructed by some implicit observer who notices the direction as well as the range of the camera focus. Cameras are therefore remote sensors. They may be mounted on some pole in order to change their field of view, or they may be moved around some spot in focus. In the former case, we move the focus while keeping the location of the camera (and thus, the location of measurement). In the latter case, we change the location of measurement, while keeping the location of the focus. For example, when we walk by a building and take photos of its front from different angles.

Satellites as well as modern digital cameras are slightly different, because they actually consist of thousands of sensors, several ones (one for a color spectrum) for each pixel. Each one of these sensors is a remote sensor. Together, they are like cameras whose exposure events are synchronized and whose foci are spatially configured in a grid. The *instantaneous field of view* (IFOV) is the angle of view of a single sensor. Multiplied by the distance to the reflecting surface during the exposure event, it allows to estimate the spatial area of the *resolution cell*. It precisely corresponds to the spatial resolution of a single raster data item.

The abstract reference space to which the raster data sets draw our attention is an abstract space of intensities of light spectrum ranges or colors.

A formal model of this example annotated by an RDF version of our theory is depicted in Figure 8.

4.2. Temperature sensors

Heat temperature sensors, such as thermometers, are devices which measure temperature at the spot where the sensor is located for a time interval defined by the temperature recording event, which takes place on the device. The focus to

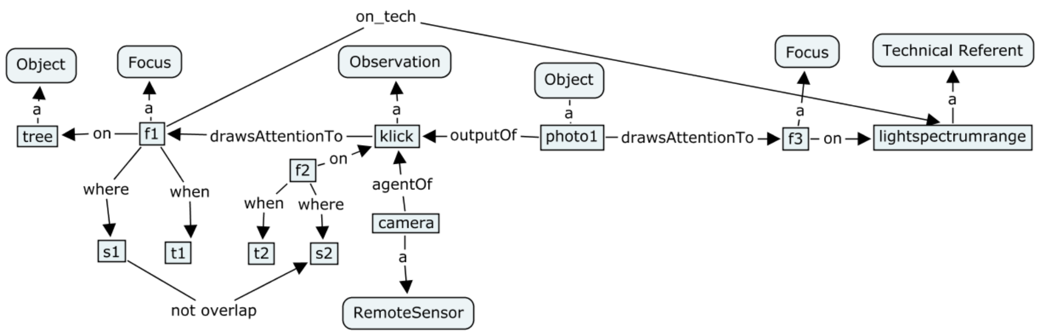


Figure 8: A formal model of a camera observation annotated with an RDF version of our theory.

which this event draws attention is also exactly on this device, and thus overlaps with the location of the recording event. Temperature measurements are therefore in-situ observations.

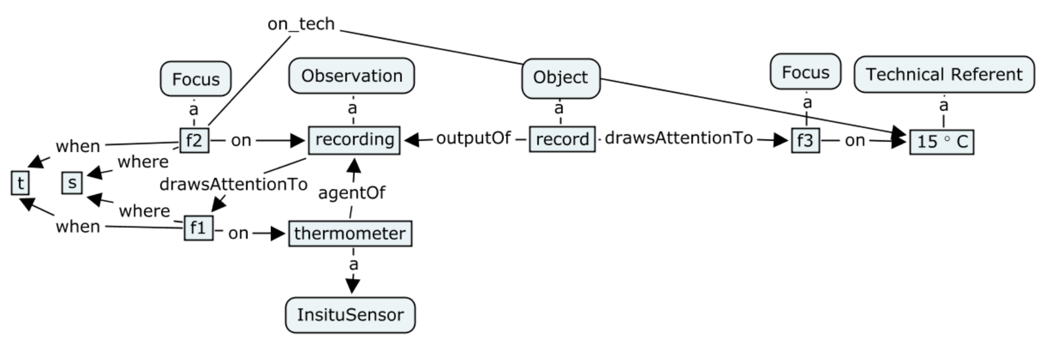


Figure 9: A formal model of a thermometer observation annotated with an RDF version of our theory.

In consequence, the spatial resolution of a temperature record is the location of the device during observation, and the temporal resolution is the recording interval. The abstract space to which temperature measurements draw our attention is the space of a temperature scale, such as degree Celsius. Humans extend their sense of temperature by acting *as if* the focus on the device was actually on the referent of the temperature scale. Their normal sense of temperature, in contrast, is a perceptual phenomenon on which they can directly focus inside their window of attention.

5. Possible applications and future work

The proposed vocabulary makes explicit the attentional processes and their participants involved in a sensor measurement. It enables to describe and document human as well as technical observation processes in a single approach. We see four major application areas:

5.1. Automated classification of data

The definitions introduced in this chapter can be used to automatically classify sensor data which was annotated using our vocabulary. Definitions describe the observation context of this data, such as observation, measurement, sensor, calibration, spatio-temporal resolution and support, as well as in-situ and remote sensors. They allow to decide, e.g., whether a data set was generated by a measurement using some sensor calibrated to some particular standard, what exactly its spatio-temporal resolution is, and whether a sensor is remote or in-situ.

In order to do so, definitions have to be translated into a form which allows to compute classifications. This can either be done by translations into decidable language standards in the Semantic Web (Janowicz and Hitzler, 2012), or by providing some algorithm which does this on a case-to case basis. Both can be considered future work. In Stasch et al. (2014), we have shown a way how data sets can also be classified based on underlying observation procedures, allowing to link data to appropriate analysis tools.

5.2. Sensor discovery and observer description

Sensors are distributed over the environment but can be linked via common interfaces to the Web. Our vocabulary can be used to describe such sensors in great detail, e.g., regarding calibration standards, abstract reference spaces, technical foci and spatio-temporal resolution, as well regarding the location of observation events and sensors at different times. It could even be used to encode the devices used to measure space and time of some observation event. The flexibility of using foci as referents with space and time extensions makes it possible to describe the movement of sensors as well as the moving of a sensor focus, e.g., the shifting of a camera focus. Analogously, one may describe attentional shifts and movements of human observers.

This flexibility allows discovering sensors on the Web based on their focus. An RDF version of our vocabulary may be used to annotate sensors and to perform queries, using standard linked data technology (Sheth et al., 2008). For example, one may search for sensors which are currently focused on a certain location in space or on some object.

5.3. *Data discovery and comparison*

Instead of annotating sensors, one can also annotate observation data with our vocabulary. One could state, e.g., that a certain data set is output of some observation event in which a certain sensor was involved which focused during that event on a certain location or on a certain object from a certain angle. This allows to compare data not only based on the involved devices, but also in terms of the configuration of participants in observation processes. For example, one could find data which depicts a certain building from a single or from different angles at different times, using daylight or infrared light-wave spectrums.

5.4. *Intention of measurement*

Making explicit the attentional process behind measurement is the first step in order to capture the intention of some scientist deploying some sensor on a specific spot of the environment (Couclelis, 2009). In future work, one may use our approach to describe the purpose of a measurement in this sense.

6. Conclusion

In this chapter, we have argued that the meaning of data produced by sensor technology can be described more adequately in terms of attentional processes, rather than technological ones. Based on the cultural relevance of joint attention, we have argued for the view that sensors can be regarded as artificial limbs for human attention. We have suggested that the technical extension of human attention by sensors is realized in terms of a metaphorical schema. In this schema, an observation event draws the attention of some implicit observer, in a twofold triadic way, to the technical focus of its technical device as well as to some referent which is denoted by its symbol output. We formalized this schema in terms of a HOL theory, provided a simplified RDF version, and introduced formal definitions of calibration, attention extension, time and location of observation, spatio-temporal resolution and in-situ and remote sensing. We discussed these suggestions based on the examples of camera and temperature sensors. We furthermore sketched future research which may apply our approach to sensor and data discovery, as well as to automated classification.

References

Botts, M. and A. Robin, eds. (2007), *OpenGIS Sensor Model Language (SensorML) Implementation Specification. OGC 07-000.* Open Geospatial Consortium Inc., URL `http://portal.opengeospatial.org/files/?artifact\_id=21273`. Accessed 22 March 2011.

Boumans, M. (2005), "Measurement outside the laboratory." *Philosophy of Science*, 72, 850–863.

Bröring, A., J. Echterhoff, S. Jirka, I. Simonis, T. Everding, C. Stasch, S. Liang, and Rob Lemmens (2011), "New Generation Sensor Web Enablement." *Sensors*, 11, 2652–2699.

Carstensen, K.-U. (2007), "Spatio-Temporal Ontologies and Attention." *Spatial Cognition and Computation*, 7, 13–32.

Chang, H. (2004), *Inventing temperature. Measurement and scientific progress*. Oxford University Press.

Compton, M., P. Barnaghi, L. Bermudez, R. Garcia-Castro, O. Corcho, S. Cox, J. Graybeal, M. Hauswirth, C. Henson, A. Herzog, V. Huang, K. Janowicz, W. David Kelsey, D. Le Phuoc, L. Lefort, M. Leggieri, H. Neuhaus, A. Nikolov, K. Page, A. Passant, A. Sheth, and K. Taylor (2012), "The ssn ontology of the w3c semantic sensor network incubator group." *Web Semantics: Science, Services and Agents on the World Wide Web*, 17, 25 – 32.

Corcho, O. and R. García-Castro (2010), "Five challenges for the Semantic Sensor Web." *Semantic Web*, 1, 121–125.

Couclelis, H. (2009), "The abduction of geographic information science: transporting spatial reasoning to the realm of purpose and design." In *Proceedings of the 9th international conference on Spatial information theory*, COSIT'09, 342–356, Springer-Verlag, Berlin, Heidelberg.

Degbelo, A. and W. Kuhn (2012), "A Conceptual Analysis of Resolution." In *XIII GEOINFO, Brazilian Symposium on Geoinformatics, Campos do Jord ao*, 11–22, Sao Paolo, Brazil.

Eco, U. (1977), *Zeichen. Einführung in einen Begriff und seine Geschichte*. Suhrkamp, Frankfurt am Main.

Eco, U. (2000), *Kant and the Platypus. Essays on Language and Cognition*. Vintage, London.

Glasersfeld, E. v. (1981), “An attentional model for the conceptual construction of units and number.” *Journal for Research in Mathematics Education*, 12, 83–94.

Glasersfeld, E. v. (1995), *Radical Constructivism: A Way of Knowing and Learning*. The Falmer Press, London.

Gray, J., D.T. Liu, M.A. Nieto-Santisteban, A.S. Szalay, D.J. DeWitt, and G Heber (2005), “Scientific data management in the coming decade.” *CoRR*, abs/cs/0502008.

Hey, T., S. Tansley, and K. Tolle, eds. (2009), *The fourth paradigm. Data-intensive scientific discovery*. Microsoft Research, Redmond, Washington.

International Standardization Organisation (ISO), ed. (2011), *ISO 19156:2011 Geographic information - Observations and measurements*. International Standardization Organisation (ISO).

Janowicz, K. and P. Hitzler (2012), “The digital earth as knowledge engine.” *Semantic Web Journal*, 3, 213–221.

Johnson, M. (1987), *The Body in the Mind. The Bodily Basis of Meaning, Imagination and Reason*. The University of Chicago Press, Chicago.

Kamlah, W. and P. Lorenzen (1996), *Logische Propädeutik. Vorschule des vernünftigen Redens*, 3rd edition. J.B. Metzler, Stuttgart, Weimar.

Kaplan, F. and V. V. Hafner (2004), “The challenges of joint attention.” *Interaction Studies*, 7, 67–74.

Köhler, W. (1992), *Gestalt Psychology. An Introduction to new Concepts in Modern Psychology*. Liveright, New York.

Lakoff, G. (1990), *Women, fire and dangerous things: What categories reveal about the mind*. Univ. of Chicago Press, Chicago.

Langacker, R.W. (1987), “Nouns and verbs.” *Language*, 63(1), 53–94.

Langacker, R.W. (2005), “Dynamicity, fictivity and scanning. the imaginative basis of logic and linguistic meaning.” In *Grounding Cognition. The Role of Perception and Action in Memory, Language and Thinking* (D. Pecher and A. Zwaan, eds.), 164–197, Cambridge Univ. Press, Cambridge.

Lehar, S. (2003), *The world in your head. A Gestalt view of the mechanism of conscious experience*. Lawrence Erlbaum Associates, Mahwah, London.

Lorenzen, P. (1964), "Wie ist die Objektivität der Physik möglich?" In *Methodisches Denken*, 142–151, Suhrkamp, Frankfurt a. M.

Marchetti, G. (2006), "A presentation of attentional semantics." *Cognitive Processsing*, 7(3), 163–194.

Marchetti, G. (2009), "Studies on time: a proposal on how to get out of circularity." *Cognitive Processsing*, 10, 7–40.

Peacocke, C. (2005), "Joint attention: Its nature, reflexivity, and relation to common knowledge." In *Joint Attention: Communication and Other Minds*, 298–324, Oxford University Press.

Probst, F. (2008), "Observations, measurements and semantic reference spaces." *Applied Ontology*, 3, 63–89.

Pylyshyn, Z.W. (2007), *Things and Places. How the Mind Connects with the World*. The MIT Press, Cambridge, Massachusetts.

Scheider, S. (2012), *Grounding geographic information in perceptual operations*, volume 244 of *Frontiers in Artificial Intelligence and Applications*. IOS Press, Amsterdam.

Scheider, S. and W. Kuhn (2011), "Finite relativist geometry grounded in perceptual operations." In *Spatial information theory: 10th international conference, COSIT 2011*, LNCS 6899, 304–327, Springer, Berlin.

Scholl, B.J. (2001), "Objects and attention: the state of the art." *Cognition*, 80, 1–46.

Sheth, A., C. Henson, and S.S. Sahoo (2008), "Semantic sensor web." *Internet Computing, IEEE*, 12, 78–83.

Stasch, C., S. Scheider, E. Pebesma, and W. Kuhn (2014), "Meaningful spatial prediction and aggregation." *Environmental Modelling & Software*, 51, 149 – 165.

Talmy, L. (2000), “The windowing of attention in language.” In *Toward a Cognitive Semantics - Vol. I* (L. Talmy, ed.), 257–309, The MIT Press, Cambridge, Mass.

Tomasello, M. (1999), *The cultural origins of human cognition*. Harvard University Press, Cambridge, MA.

VanRullen, R. and C. Koch (2003), “Is perception discrete or continuous?” *Trends in Cognitive Sciences*, 7, 207–213.