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Closing the Loop between Knowledge Patterns in Cognition and the Semantic Web

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Abstract. This article discusses currently open issues in the discovery and representation of knowledge patterns in computational processing of meaning. Starting from a formal semantics for *knowledge patterns* as discussed in cognitive science and knowledge representation, some measures are suggested to improve interoperability and validity of web-based semantics.

Keywords: Relations, Roles, Frames, Knowledge Patterns, Cognitive Semantics, Interoperability

1. A Design Loop

After 20 years of Semantic Web, at least 60 years of attempts to build computational models of meaning, and 100 years from the publication of Ludwig Wittgenstein's *Tractatus Logico-Philosophicus* [50], let alone the previous footwork of philosophers, linguists, and logicians, the situation with publicly shared, rigorous representations of meaning is only partly satisfying. The deep learning turn in artificial intelligence is adding new means for inductive inference and pattern discovery, but not much to the general problem: what are the basic bricks of meaning, if any, and their viable computational representation? How to make them converge (or diverge) according to the needs for local efficacy and global interoperability?

In work presented in 2010 for the inaugural issue of this journal [19], those building blocks were identified in *Knowledge Patterns* (KP) [6][13], a semantic web generalisation of *frames* in cognitive science, linguistics, and sociology literature, which have played a substantial role in early knowledge representation. The proposed approach was to empirically collect and use KPs for design, re-engineering and interoperability across data, schemas, lexicons, and interaction.

While in 2010 the amount of known KPs was limited to certain well known ontology design patterns [13][41] and informal linguistic frames, with examples of how different data models and data structures could be made interoperable through them, from that time some advancements have been made, which are briefly summarized in Sect. 3.

It is now time to assess where we are, and to take another step towards an integration of scientific efforts from superficially unrelated disciplines ranging from cognitive neuroscience to knowledge representation.

2. KP as Multigrade Predicates

As Dedre Gentner [23] stated in a crystalline way:

> the ability to perceive and use purely relational similarity is a major contributor –arguably the major contributor– to our species' remarkable mental powers.

Gentner's quotation gives us a starting point to propose a dual nature for knowledge patterns and relations: on one hand, they are intensional structures that char-

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acterise certain invariant features of the world, making specific situations emerge out of the continuum of reality as perceived, memorised, and publicly recognised in human societies and individuals. On the other hand, they are extensional relations with a precise extensional semantics. The orderly view of relations corresponds to the cognitively reified view of knowledge patterns, and viceversa. Feature similarity helps detecting a relation that has been already sensed in the past, as well as recognising a pattern that has been already stored in bodily, societal, and cultural memory.

The Semantic Web has started as a pragmatic way to use the Web as a platform to spread human semantics and human ability to process meaning. That platform was supposed to be decentralised, and to (unintentionally) realise the dream of a transparent negotiation of meaning, where entities have a public identity, with publicly known features that are encoded in public representations that can be dereferenced on the Web.

Eventually, the Semantic Web has created the conditions for web semantics to evolve: billions of multi-domain Linked Data triples, the international acceptance of governmental linked open data, the FAIR data movement, and the crucial asset development for enterprise knowledge graphs, are all evidence for a paradigm shift. Yet, where real semantic interoperability has succeeded, it has typically happened in a centralised way. Some examples are shown here:

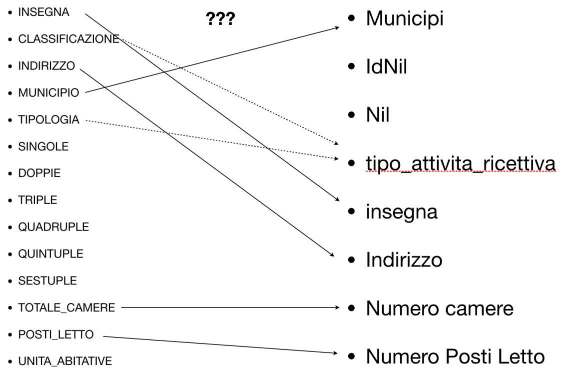

Fig. 1.: The uncertain/incomplete mappings between two simple schemas for accommodations from Rome vs. Milan municipality data.

- public administrations produce data with heterogeneous schemas, even for simple conceptualisations such as accommodations in Rome and Milan (Fig. 1): only centralised efforts to create shared schemas, and complex refactoring procedures after data ingestion, are able to alleviate the problem;[1]
- web designers and content producers use their own tags, and only something like schema.org has enabled SEO and semantic search to take off;
- DBpedia has evolved a large schema for Wikipedia data that is partly dependent on Wikipedia Infoboxes, partly on collaborative design of classes and properties, however, data needs cleaning, and only a stronger semantics as shown in [38] is able to detect the most severe problems emerging from bulk reengineering practices;
- the decision making on sharing schemas is painful and subject to conflicts, let alone the cases when generic schemas, which are independent from an organisation's control, and do not necessarily cover the same semantics, are nonetheless assumed as standard. A proper practice may be instead to analyse the requirements extracted from scenarios or competency questions, as recommended by state-of-the-art agile methods such as eXtreme Design [42], and only later to align the resulting ontology to existing ones;
- a large amount of knowledge needs to be extracted from natural language, but the integration between natural language understanding, which is progressing towards a shareable semantic representation, AMR [3], and ontology design is not yet widespread, despite the road has been opened by knowledge extraction methods [**?**] and massive integration of linguistic and factual resources [15].

Notwithstanding the long (10 years) activity of the Ontology Design Patterns community, with the substantial work collected in repositories such as `http://www.ontologydesignpatterns.org`, or published (cf. [27], let alone the general agreement on reusing design patterns in ontology design for the Semantic Web and Conceptual Modelling [11], ontologies usually do not include their design practices, and modeling choices are scarcely documented, leading to difficulties in integrating schemas and their data. Even the FrameBase approach [43], which practically implements interoperability based on FrameNet frames as hubs for alternative schemas sharing a KP, does not

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[1] Cf. the DAF platform supported by the OntoPiA ontology network in Italy `https://github.com/ontopia/ontopia`

yet look as a real game-changer, possibly due to its limited coverage.

Clearly, there is a difficulty in abstracting from local modeling choices, without a strong centralization, or a push towards the reuse of a quasi-standard. The reason probably lies in both the distance between domain expertise and ontology design practices, which require non-trivial logical competence, and in the existence of alternative terminologies, design solutions, and local alternatives, which make different but potentially overlapping schemas look farther than they actually are.

Semi-automated ways to design ontologies, to match them, or to inject interoperability, are still on the academic side of things, probably because of their limited friendliness or conceptual coverage.

The suggestion here is to take the bull by the horns, which in this case means to start a widespread collection of knowledge patterns where they actually are: existing ontologies, data models, large natural language corpora, linguistic resources, competency questions from formal and informal contexts, workflows, how-to repositories, commonsense knowledge bases, etc. The knowledge patterns emerging from this activity need to be intensional, and to be annotated with their compositional paths. Here both deductive and inductive techniques, jointly with usage of large multilingual knowledge graphs, must help (cf. Sect. 5).

While KPs should preserve their intensional nature, and avoid a strong commitment to specific logical primitives, a minimal correspondence between intensional and extensional axioms can be maintained by using Framester semantics, described in the following.

2.1. Knowledge Patterns as Multigrade Predicates: the Framester KP Semantics

In search for logical neutrality, we propose here an abstract notion of relational representation across natural languages, logics, data structures, applications, neuroscience. The first intuition came from so-called *multigrade predicates* [37]. A multigrade predicate is a polymorphic n-ary relation. It can have multiple arities (in neo-Davidsonian terms, cf. [7]), and can have *place labels* that “overtype” a binary projection of the predicate. The mapping from linguistic semantics such as Tesnière’s *stemmata* [45] –which led to *valencies* in dependency grammars– or Fillmore’s *conceptual frames*[2], to multigrade predicates, is straightforward. Relevant distinctions such as *actantial* vs. *circumstantial* complements (Tesnière), *core* vs. *peripheral* roles (Fillmore), etc., could be represented as (sets of) places. Web formats: XML stylesheets, templates, microdata, infoboxes, JSON objects, etc. can all be represented by predicates and places.

Multigrade predicates and their places have a close resemblance to an ontology design framework called Descriptions and Situations (D&S) [17,14,20], which was originally intended as a two-tier modelling of the extensional and intensional semantics of predicates, with a focus on events or situations. The motivating use cases were in legal and medical ontologies, where we need to talk both about the world (e.g. organic or social facts), and about the way we observe or categorize them (e.g. a clinical condition or a legal norm).

In the early times of the Semantic Web, separating intensional and extensional modelling needed a duplication of constants in a vocabulary, e.g. `ViralHepatitis` had to be represented with two different constants for talking about its roles/places (its definition), and for its occurrences (its instantiated situations). Later on, OWL2 [31] *punning* mechanism enabled the usage of a same constant for the two functions, and the resulting ontologies are much simpler.

D&S has been applied in order to generalise any kind of knowledge pattern into a formal two-tier semantics, as in the Framester factual-linguistic knowledge graph [15].

A KP is defined as a multigrade predicate $\phi(e, x_1, ..., x_n)$, where ϕ is a first-order relation, e is a situation variable described by a KP, and x_i is a variable for any argument place. Now, using D&S-style OWL2 punning, we introduce ϕ as a knowledge pattern from class `KP` and a subclass of `SIT` (*situations* i.e. KP occurrences/observations, (1-2)), ρ as a binary or unary KP projection of multiple types (semantic roles (3), co-participation relations (4), or types (5), ι as individuals occurring in a situation (6), τ as binary tuples occurring in (the projection of) a situation (7), and ω as expressions from a class `EXP` denoting (“θ^{sit}”, (8)) an occurrence of a KP ϕ in a KP composition Φ, assuming that (in general) ω is capable of evoking (“θ^{kp}”, (9)) ϕ.

$$\forall(\phi)\texttt{KP}(\phi) \tag{1}$$

$$\forall(s)\phi(s) \leftrightarrow \texttt{SIT}(s) \tag{2}$$

$$\forall(s, x_i)\rho^{rol}(s, x_i) \rightarrow \phi(s, x_1, ..., x_n) \quad [i \geq 1 \leq n] \tag{3}$$

$$\forall(s, x_j, x_k)\rho^{cop}(x_j, x_k) \rightarrow \phi(s, x_1, ..., x_n) \quad [j \geq 1 \leq n, k \geq 1 \leq n] \tag{4}$$

$$\forall(s, x_m)\rho^{typ}(x_m) \rightarrow \phi(s, x_1, ..., x_n) \quad [m \geq 1 \leq n] \tag{5}$$

$$\forall(\iota)\rho^{typ}(\iota) \rightarrow \phi(s, x_1, ..., x_n) \quad [\iota = x_1 \cup ... \cup \iota = x_n] \tag{6}$$

$$\forall(\tau)(\rho^{rol}(\tau) \rightarrow \exists(s, x_i)(\rho^{rol}(s, x_i)) \cup (\rho^{cop}(\tau) \rightarrow \exists(x_j, x_k)\rho^{cop}(x_j, x_k)) \tag{7}$$

$$\forall(\omega)\texttt{EXP}(\omega) \leftrightarrow \exists(\phi)\theta^{kp}(\omega, \phi) \tag{8}$$

$$\forall(\omega, s, \phi, \Psi)\theta^{sit}(\omega, s, \phi, \Psi) \rightarrow \theta^{kp}(\omega, \phi) \wedge \phi(s) \quad [\phi \in \Psi] \tag{9}$$

As detailed in formulas (1) to (9), Framester KP semantics is a formalisation of meaning interpretation in context, which bears from:

- multigrade predicates theory: ϕ is polymorphic and has typed places;
- Fillmore's frame semantics: symbols evoke frames, which have semantic roles with values having a certain type (types are used as selectional restrictions in certain lexical semantic theories, such as VerbNet [29]);
- D&S: predicates have a two-tier intensional and extensional semantics, encoded with the help of OWL2 punning

Framester KP semantics has also original features in:

- representing *projections* of a KP as *roles* of polymorphic relations, as *co-participation relations*, or as *types*, which are also frames on their turn;
- distinguishing *a-priori evocation*: an expression evokes a KP, vs. *applied evocation*: an expression is used in context and evokes a situation, in which multiple KPs could be evoked, and composed.

A shortened example of Framester KP semantics is provided here with a description logic representation of frames, semantic roles, types, projections, individuals and tuples evoked by the sentence: *this jacket is made of cotton*[2].

$$\texttt{Clothing} \in \texttt{KP} \tag{10}$$

$$\texttt{Causation} \in \texttt{KP} \tag{11}$$

$$\texttt{Substance} \in \texttt{KP} \tag{12}$$

$$\texttt{Jacket.n.1} \sqsubseteq \texttt{Clothing} \tag{13}$$

$$\texttt{Make\_26010000} \sqsubseteq \texttt{Causation} \tag{14}$$

$$\texttt{Cotton.n.1} \sqsubseteq \texttt{Substance} \tag{15}$$

$$\texttt{Jacket.n.1} \in \rho^{typ} \tag{16}$$

$$\texttt{Make\_26010000.Theme.Material} \in \rho^{cop} \tag{17}$$

$$\texttt{Make\_26010000}, \texttt{Make\_26010000.Theme.Material} \in \zeta \tag{18}$$

$$\texttt{Cotton.n.1} \in \rho^{typ} \tag{19}$$

$$\texttt{a.jacket} \in \texttt{Jacket.n.1} \tag{20}$$

$$\texttt{a.make} \in \texttt{Make\_26010000} \tag{21}$$

$$\texttt{a.cotton} \in \texttt{Cotton.n.1} \tag{22}$$

$$(\texttt{a.make, a.cotton}) \in \texttt{Material.make\_26010000} \tag{23}$$

$$(\texttt{a.make, a.jacket}) \in \texttt{Theme.make\_26010000} \tag{24}$$

$$(\texttt{a.jacket, a.cotton}) \in \texttt{Make\_26010000.Theme.Material} \tag{25}$$

$$\textit{jacket} \in \texttt{EXP} \tag{26}$$

$$\textit{made} \in \texttt{EXP} \tag{27}$$

$$\textit{cotton} \in \texttt{EXP} \tag{28}$$

$$(\textit{jacket}, \texttt{Jacket.n.1}) \in \theta^{kp} \tag{29}$$

$$(\textit{made}, \texttt{Make\_26010000}) \in \theta^{kp} \tag{30}$$

$$(\textit{cotton}, \texttt{Cotton.n.1}) \in \theta^{kp} \tag{31}$$

$$(\textit{jacket}, \texttt{Jacket.Make.Cotton}) \in \theta^{sit} \tag{32}$$

$$\texttt{Jacket.Make.Cotton} \sqsubseteq \texttt{Clothing.Causation.Substance} \tag{33}$$

$$\texttt{Clothing.Causation.Substance} \equiv (\texttt{Clothing} \otimes \texttt{Causation} \otimes \texttt{Substance}) \tag{34}$$

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[2] For space reason, we do not include the OWL code with namespaces, but the predicates used are all from the Framester knowledge graph, which can be downloaded and queried from `https://github.com/framester/Framester`

The high amount of axioms for this example may seem against Ockham's razor, a venerable principle in knowledge representation. But they are produced because of the need to have a two-tier (extensional+intensional) representation: most of them can be generated automatically out of a general intensional template for the three disambiguated KPs (`Jacket.n.1`, `Make_26010000`, `Cotton.n.1`), jointly with the knowledge from Framester, and the support of a semantic parser in the case of natural language (e.g. FRED[22][3] produces knowledge graphs that are ready to be extended with Framester semantics). The advantage of this intensional generalisation is quite obvious: no special knowledge representation language is required, but any design choice for e.g. a *make* concept (an object property from an ontology, a datatype property from a database refactoring, a class from another ontology or a JSON microformat, an individual from a linguistic ontology, etc.), can be all aligned using both ontology and linguistic matching techniques, once the intensional disambiguation has been performed.

3. KP and Cognition

The term *knowledge pattern* was firstly introduced by de Beaugrande [8]:[4]

> the availability of global patterns of knowledge cuts down on non-determinacy enough to offset idiosyncratic bottom-up input that might otherwise be confusing.

However, the idea of recurrent, invariant units of knowledge was already present in philosophy, psychology and sociology as *schemata*, at least since [39]:

> La logique égocentrique est plus intuitive, plus «syncrétique», que déductive ... Elle emploie des schémas personnels d'analogie, souvenirs du raisonnement antérieur, qui dirigent le raisonnement ultérieur sans que cette influence soit explicite.[5]

Notably, in the same period (1970-1980) more notions were being introduced to characterize cognitive structures that were supposed to abridge research in linguistics, artificial intelligence, knowledge representation, etc. These include *Frames* in linguistics [12], later defined in FrameNet[6] as:

> a schematic representation of a situation involving various participants, props [inanimate entities, *ed.*] and other conceptual roles, each of which is a frame element

and in artificial intelligence [30], defined as:

> a remembered framework to be adapted to fit reality by changing details as necessary ... a frame is a data-structure for representing a stereotyped situation.

Macrostructures [47], defined as:

> higher-level semantic or conceptual structures that organise the 'local' microstructures of discourse, interaction, and their cognitive processing.

Scripts [44], defined as:

> a structured representation describing a stereotyped sequence of events in a particular context.

As de Beaugrande noticed about those different notions, "*These large-scale knowledge configurations supply top-down input for a wide range of communicative and interactive tasks.*". In fact, there seems to be a common intuition concerning *invariances* shared by multiple situations, typically featuring an internal order, and being applied to multiple reasoning and interaction activities.

Since something can be invariant only if it remains unchanged under transformations[7] that span through time, space, observers, physical conditions, constituency, measurement, procedural constraints, etc.,[8] and since knowledge patterns are representations of situations, they reflect that those situations remain unchanged under some transformation of features that are not relevant for the pattern to be applicable (they "offset idiosyncratic bottom-up input").

For example, a red ball might still be a red ball after being deflated, but a red ball to play volley cannot. Throwing paper waste on the street may be the same action on any street, but in a country the same action can be tolerated, in another not. A slap is a slap, but it could be voluntary or not, an aggression or a joke, according to the intention of who's slapping, or to the observer's perspective.

Knowledge patterns contain invariant features that make them appropriate as abstract data structures to be remembered/stored, and, as Minsky [30] noticed about frames, they can be *adapted to fit reality by changing details as nec-*

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[3] Use this API for an example: `http://wit.istc.cnr.it/stlab-tools/fred/demo`

[4] A close usage of the term can be found earlier in a "creative engineering" book [36]: "*knowledge pattern ... by this is meant the knowledge and experience applicable to the technique of synthesis ... There are three important parts to the knowledge pattern as regards creative work, (1) scientific knowledge, (2) design curiosity, and (3) the ability to generalize experience.*"

[5] "Egocentric logic is more intuitive, more "syncretic", than deductive ... It uses personal patterns of analogy, memories of previous reasoning, which direct the subsequent reasoning without this influence being explicit."

[6] `https://framenet.icsi.berkeley.edu/fndrupal/glossary`

[7] Cf. Paul Dirac [9]: *"The important things in the world appear as invariants ... of ... transformations"*.

[8] Cf. [32] for a detailed study on invariance and objectivity, and [24] for Gibson's psychological theory of how invariances in stimulus-energy pair permanent ("projectable") properties in the environment ("affordances").

essary. Minsky's intuition can be used to propose KP dynamics as a pendulum swinging between invariances (tending to universal patterns) and localities (tending to pattern divergence, adaptation or blending). Cognition works with patterns, but updates them to local observations, which are unique, because of the richness and compositional interference of actual (multi-modal) perceptions. This tension is reflected also in Barsalou's simulation theory [4], which can be summarised as the defense that concepts are *grounded* by multi-modally-informed, situated simulations of the external world. Barsalou [5] also proposes that concepts can be shared thanks to a huge *coordination activity* aimed at establishing a common ground for mutual understanding.

This is backed by neurological results. A recent fMRI metastudy by David Wisniewski [49], starting from the following dilemma:

> Some suggested that intentions representations in the fronto-parietal cortex change flexibly when external demands change (context-dependent coding). Others suggested that these representations are encoded in an abstract format that is not affected by changes in external demands (context-invariant coding)

revisits the literature on goal-oriented action and context, and finds that:

> results to date are mixed, showing context-dependence in some, but context-invariance in other cases ... depending on characteristics of intentions as well as environment, intentions can either be encoded in a context-dependent or a context-invariant format ... to achieve both stability and flexibility of behavior under constantly changing external demands

Two questions emerge then for a computational treatment of knowledge patterns: what features characterize a pattern? how to be tolerant to pattern adaptation?

On one hand, since patterns have inherent invariances, they are useful to make predictions, to create expectations, to quickly judge something, to catch opportunities (affordances), to avoid obstacles, to diagnose a medical condition, to hypothesize a natural law, to establish a social norm, to maintain a physical, social, or individual equilibrium, etc. This massive importance make them key to interoperability across multiple representations.

On the other hand, in many contexts a pattern can be used analogically, approximately, partially, while still retaining some of its explanatory power. In other words, patterns retain their usefulness even when they do not fully correspond to a situation.

An extreme case happens when a KP is used to denote the special or unique quality of a situation, e.g. when a politician has a lot in common with a sportsman, or a gangster (cf. the cases described in a Wikipedia pattern exploration of knowledge patterns emerging out of Wikipedia links [35]), or when one recognizes the unique way of nodding by a friend, or notices an original way of playing a saxophone, as in Anthony Braxton's deconstructionist interpretation of Charlie Parker's Ornithology:[9] it a quite conservative jazz rhythm section part, but there are unique features (sound, articulation, timing, harmonic freedom) that make that track unique (uniqueness prizes "idiosyncratic bottom-up input").

In addition, due to their tolerance to modification, knowledge patterns have a dynamics: they are *adaptable* (e.g. when applying a `Too Much` frame to food consumption, sunlight, or amusement), can be *learned* or *discovered* by a human or a machine from a collection of examples (e.g. when learning the visual aspects of a saxophone, or the possible configurations of a live jazz performance), can be extended or mapped to other contexts (e.g. when using a `climax` script as a metaphor for a musical performance).

As evident in the `Too Much` frame applied to the `Food Consumption` vs. the `Amusement` scripts, knowledge patterns have a peculiar compositionality, which requires specific means for a computational treatment.

4. KP Compositionality

Knowledge Patterns, variously called schemas, frames, scripts, scenes, modeling components, data modeling patterns, etc., have been proposed as the core building blocks in ontology design [19], providing cognitive relevance, explicit situation boundaries, independence from a particular formalism, under the assumption of direct associations to modeling requirements. For example, in the classic blocks world example of AI, a generic $\texttt{Over}(o_1, o_2)$ frame involving a vertical spatial relation between any two physical objects satisfies a modeling requirement that only takes into account the relative position of the objects. However, if the requirements include the knowledge whether the two objects touch each other or not, a richer $\texttt{On/Above}(o_1, o_2, c)$ frame that requires a role for the contact situation will be needed. The richer frame is actually the composition of $\texttt{Over}(o_1, o_2)$ with the $\texttt{Contact}(o_1, o_2, c)$ frame.

A KP can be represented in a specific logical language, but it should also preserve an intensional representation that is invariant across logical languages. In their original presentation of KPs in knowledge representation, Peter Clark and colleagues [6] indicated category theory as the most adequate abstraction for KP representation. More recently, Oliver Kutz and colleagues [10] chose a close approach for the representation of conceptual blending. Our intention here has been to start from a more traditional mathematical framework, close to existing KR languages: a two-tier intensional/extensional logic, which can use the same basic semantic web languages in use today (cf. Sect. 2).

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[9] `https://www.youtube.com/watch?v=PuoBeYB-O1M`

For example, a `Playing Music` KP (represented here as a first-order multigrade predicate for brevity) (35),

$$\texttt{PM}(p, i, c, t, tim, loc) \tag{35}$$

with role projections (ρ^{rol}) such as player, instrument, composition, tempo, time, location, etc. Selectional constraints (ρ^{typ}) [48] could be added to those roles, e.g. a player should be a person, an instrument should be tempered, a composition should be in written form, a tempo should be in a certain range, etc. However, specific applications of `Playing Music` might force roles to accept an untempered musical instrument, an AI playing a part, a section that is not written, but improvised, etc.

`Playing Music` could also be used to refer to a metonymically related situation, e.g. when one plays music *on* an audio system: in this case interpretation needs to reconstruct a composition of default music playing, its recording, and its reproduction. We may want to treat this as two separate `Playing Music-1` and `Playing Music-2` frames, but `Playing Music-2` is the result of a composition depending on `Playing Music-1`.

Literature on compositionality is huge (cf. [26] for a recent palette of positions), but the basic argument is about the asymmetry between symbolic and semantic compositionality: *is the meaning of a structure entirely determined by the meaning of its constituents*? There are multiple reasons why the answer is “not always”.

We can consider five classes of asymmetry, with examples from natural language texts: (1) anaphoric composition: *They got* ***married. She*** *is beautiful*; (2) modal composition: *23-year-old man dies after* ***fake doctor*** *administered unidentified treatment via injection*; (3) hidden relations: *this* ***plaid jacket with hood*** *is made of cotton*; (4) world structure: ***cutting a cake*** vs. ***cutting the grass***; (5) metaphoric composition: *Breaking point: why the Kyrgyz* ***lost their patience***. In all five cases, entailment, perspective, background or commonsense knowledge, or blending [10], [16], need to be supplemented in order to finalise semantic composition.

In practice, all those cases are more or less easily composed by people, despite their asymmetry: what is lacking to computational semantics to approximate that ability? Our hypothesis is that KP compositionality is lacking.

Currently, we have sophisticated logical compositionality within ontologies: classes are associated with other classes via properties or taxonomical relations, properties are associated with other properties through chains, SWRL, or SPIN rules, classes are associated to properties via domains and ranges, or restrictions. We have an ontology compositionality via ontology import. We even have vectorial compositionality in vector space models of semantics [46], now enriched by embedding and deep learning techniques.

But we do not have any compositional machinery, let alone an algebra, to compose knowledge patterns. The most we can do is to represent KPs in ontology modules (or alternatively in named graphs), and import them in a new ontology, or merging them in a graph.

Yet, the result of composing a KP with another is a third KP, not an ontology. We need a language to talk about intensional compositionality, jointly with a grounding into ontologies and off-the-shelf classes and properties. A beginning of such a composition style has been sketchily demonstrated in Sect. 2. We describe here in more detail how KP compositionality provides a different view on well-known problems in natural language semantics and ontology engineering.

4.1. Framality

Our assumption is that compositionality effects on formal representations of meaning derive from *framality*: basically the observation that KPs are one of the motivating forces for contextual effects, as also reported with respect to frames and their selectional restrictions in neuropsychological studies (e.g. [48]).

A notable example of framality can be given in adjectival semantics [18]. It can be defined as *the ability of an expression to evoke a KP from the joint evocation of KPs emerging during interpretation*. In the case of adjectives, a good example is the following pair of terms: *extroverted surgeon* and *skillful surgeon*. While we might represent the two terms as a conjunction:

$$\forall(x)\texttt{ExtrovertedSurgeon}(x) \rightarrow \texttt{Extroverted}(x) \wedge \texttt{Surgeon}(x) \tag{36}$$

$$\forall(x)\texttt{SkillfulSurgeon}(x) \overset{?}{\rightarrow} \texttt{Skillful}(x) \wedge \texttt{Surgeon}(x) \tag{37}$$

from (1), we can safely infer that all extroverted surgeons are extroverted in general, but from (2) we are not safe at inferring that all skillful surgeons are skillful in general. The likely reason is that `Being_skilled` is a possible value for the core aspects of the `Medical_professionals` KP, while `Being_extroverted` is not, therefore this tends to be interpreted as a frame composition. For comparison, a similar treatment for *extroverted comedian* does not allow a safe inference of being extroverted in general, while *alcoholic comedian* does.

Another example of framality can be done with reference to certain meta-properties proposed by the OntoClean methodology [25]. As an example, a property is traditionally called *rigid* when it is true for an entity during the entire course of its life. It is non-rigid otherwise. For example, the `Student` property (in the sense of being enrolled at some educational institution) can hardly be true during the entire life of a person.

However, this distinction is usually understood without taking into account locality conditions. For example, if an ontology is not interested in representing properties of entities in a forever-lasting perspective – as with a university enrolment ontology – what establishes rigidity is the temporal perspective of e.g. `Being_a_Student` frame, rather than the `Being_a_Person` frame. Within the university context, it is a property like `Enrolled_in_a_course` that is non-rigid, since the frame of that property has a shorter time span compared to that of `Being_a_Student`.

In other words, the context of meta-level properties is maximal, while framality requires contexts to be bound to requirements or local conditions. Interoperability requirements may change this sanity assumption: if university data are integrated with personal data, `Being_a_Student` would become non-rigid. Anyway, this may also apply to `Being_a_Person` if personal data are integrated with notarial data, which may include actions of a person even after death.[10].

Similar observations can be made about other meta-properties such as *phasal*, *sortal*, etc.

5. Where are we now?

What is the current state of the art in KP research? We summarize some research questions in the following.

1. what KPs are known?
2. is KP coverage enough to approximate human knowledge patterns?
3. how to extend, evolve, learn, or discover KPs?
4. how to enrich automated reasoning with an intensional characterisation of KPs?
5. how to use intensional KPs to foster interoperability independently from the local representation of an ontology or conceptual model? In other words, how to employ KPs in ontology reengineering and ontology matching?
6. what is the intensional difference between frames, roles, and selectional constraints or types)?
7. how to formalize KP compositionality?
8. how to study higher levels of semantics, such as modalities, opinion, emotions, metaphors, narratives, and other macrostructures?

This is definitely an ambitious research programme, which has been partly carried out in the last 10 years. In the next section, a quick survey is provided, while in the following, we present some proposals for a substantial growth.

Concerning known KPs and their coverage, some progress has been made, for example the Framester [15] knowledge graph is able to represent any linguistic or ontology predicate as a KP, and to reconcile it to a foundational layer initially provided by FrameNet [28] frames, and now extended to WordNet and other linguistic repositories. Hundreds of thousands of KPs have been automatically extracted from existing repositories [33],[15]. Many more KPs can be extracted from existing data [40], or informal graphs such as Wikipedia links [34].

Still, the compositionality examples shown here, the variety of situation types addressed by existing ontologies, let alone the larger societal scenarios, prove that we are still far from a systematization of KP collection, and the related ability to make use of them (FrameBase [43] has proved that interoperability is possible using KPs, and can be swiftly implemented). Another experiment has been described in [1] about reconciling different but related knowledge graphs (extracted from text), by exploiting KP embeddings and combinatorial optimisation.

Concerning KP semantics, in Sect. 2 we have summarized a long-standing investigation into the nuances of intensional KP representation. How full-fledged reasoning with KP compositionality might impact existing automated reasoning techniques, e.g. OWL2 reasoners? Could we reduce the computational complexity of knowledge graphs and their matching by counting on the schematic nature of KPs, and automated translation into existing logical languages?

An example of using KPs inherent in the DOLCE foundational ontology to clean up a knowledge graph is described in [38].

Examples of using KPs for representing higher levels of meaning are described in [21] about using two-tier semantics for extracting knowledge graphs from text, and over-describing them with opinion KPs that improve the state of the art in aspect-based sentiment analysis. Another recent example [16] is about representing conceptual metaphors as KP mappings, and attempting to use the resulting knowledge base for both detection and generation of metaphors.

Far from being complete, we have tried a check of the state of play with knowledge patterns in the Semantic Web, jointly with a review of why cognitive neuroscience can give us directions to design, extract, and use data and ontologies in the most efficient way when the problem is the computational treatment of meaning.

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