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Relation Ontology II

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Abstract. Conceived as a follow-up to recent efforts destined to supply .owl ontologies with relational tools of greater complexity, the present article focuses on four main paths, all of them consisting in providing biomedical ontologies with formal means to express (1) deviations from normality, (2) topological connectedness, (3) inherence and (4) causality and function.

Keywords. Ontology, OWL, rational reconstruction, relations, function, Systems Theory

Nature Precedings : hdl:10101/npre.2008.2479.1 : Posted 5 Nov 2008

Motivation

Ontologies are no longer confined to Philosophy. Computer scientists are nowadays eager to dip into the philosophical wisdom pool, in search for new, more expressive, and most importantly, more accurate, coherent, and consistent ways to represent reality *in its entirety*. The latter is, as a matter of fact, one of the main aspects that have propelled traditionally philosophical issues, methods and approaches, into the limelight of applied science, and that have compelled IT researchers and engineers—most of them quite reticent vis-à-vis things philosophical—to lend ears to what comes from the depths of immemorial philosophical times. It is the promise of a global approach to reality, as opposed to the parochial endeavors promoted in pre-ontological KR[2] pursuits, that gave rise to what we presently witness as “the ontological turn.” One can never overestimate the virtues of global thought, and the merits of a *Weltanschauung*, in untangling lower level scientific conundrums, and in ensuring global coherence, compatibility and interoperability.

As a result, ontologies have been hijacked and turned into another KR style, one of many. As such, in order to allow for automated maneuverability via reasoning and consistency detection tools, and in order to provide for productive inference and analysis, they have to be endowed with expressive powers well beyond what traditional ontologies were about. Traditionally ontologies were little more than taxonomies of Existence/Being, hence based on “*is a*” hierarchies (aka subsumption hierarchies). As a KR style, however, users demand more tools, capable to express more intricate relations. These tools should also be more precise and more formally specified.

This process of enhancing ontologies will preoccupy us in the following.

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[2] **K**nowledge **R**epresentation

Nature Precedings : hdl:10101/npre.2008.2479.1 : Posted 5 Nov 2008

1. Background

The present article constitutes a follow-up to the very successful [9], which sets upon the task of improving the reliability and precision of biological and medical ontologies. In short, the diagnostic put by the authors—and with which we happen to concur—is that most existing biological and medical ontologies can be bettered by adopting tools and methods inspired from formal logic and formal ontology. Such an endeavor is seen as bringing about a greater degree of rigor, which fosters interoperability and integration, and ultimately facilitates the handling of biomedical data in an efficient and unambiguous manner by both human operators and especially by automated devices.

The concrete steps undertaken in this respect by [9] consist in (a) providing a formal (and ontologically sound) support to the relations currently used in most biomedical ontologies—namely *is_a* and *part_of*, and (b) enhancing the list of such relations with new ones in order to compensate for the paucity of expressive means of said ontologies. The former undertakes a reconstruction of these two relations within the language of first-order logic (FOL), considered by the authors to be a sufficiently expressive and rather uncontroversial framework. The second aspect involved in (a) is most likely less immune to controversy as it makes use of a proprietary (though free/open-source) ontological framework known as Basic Formal Ontology (BFO), which was expounded in a series of articles by B. Smith and P. Grenon ([1]-[8]). The ontological soundness of the two relations (*is_a* and *part_of*) is thus supposed to be ensured by situating them within the larger BFO schema.

Figure 1: BFO diagram

Built against an Aristotelian backdrop, the BFO framework makes use of a basic top-level distinction ("the great divide") between two kinds of entities: substantial entities or continuants (entities that endure through time while maintaining their identity) on the one hand, and occurrents or perdurants (entities that happen, unfold, or develop in time) on the other. Corresponding to these two kinds of entities are two basic and distinct perspectives that can be taken on the world, neither of which can fully capture or represent the features of reality represented by the other: these are the SNAP and SPAN perspectives or ontologies respectively. Each of these basic perspectives can also be used to represent entities at different levels of granularity, resulting in further perspectival subdivisions of the basic SNAP and SPAN ontologies. For our purposes here, suffices to mention that the SNAP ontology recognizes three major categories of continuants: dependent continuants, independent continuants and spatial regions, while SPAN includes processual entities and spatiotemporal regions.

Step (b) proceeds by assuming a host of new primitive individual-level relations (i.e. relations between individuals)—e.g. **part_of**, **instance_of**, **located_in**, **has_agent** etc.[3] This background is then used to construct the corresponding class-level relations (i.e. relations between classes), and to define new individual-level and corresponding class-level relations. As a result, a new ontology (dubbed Relation Ontology (RO)) emerges. As of January 2007, RO comprises thirteen class-level relations (see http://obofoundry.org/ro/). It is the aim of the present article to further enhance the list of relations in RO by including relations noticeably absent so far, such as *lacks*, *has_function* etc.

Nature Precedings : hdl:10101/npre.2008.2479.1 : Posted 5 Nov 2008

2. Relations

Our efforts have been channeled on four major fronts, all of them consisting in providing biomedical ontologies with formal means to express 1) deviations from normality, 2) topological connectedness, 3) inherence and, last but not least, 4) causality and function. The latter is, above all, the area most conspicuously missing from RO as it is right now. We have assumed the same prerequisites as RO, which is to say that FOL has been our language of our choice, while BFO our background ontology. As the relations we have designed not only complement existing RO relations, but make copious use of them, it is obvious that our additions have to be consistent with RO; we are, however, not aware of any formal consistency proofs concerning RO—with or without our additions—so our focus has been targeted at designing relations which are not overtly and prominently contradictory, though this is not to say that they may not prove as such upon further investigation.

2.1. lacks_part

Meant to express a shortfall from normality (e.g. "John **lacks_part** finger"), **lacks_part** would have to be a relation between an individual and a class/universal. Introducing a relation to this effect appears, by most accounts, as imperative, as the vast majority of medical observation data is constituted by so-called "negative findings" ("lacks one kidney," "lacks sense of smell," "lacks sense of pain"—see http://ontology.buffalo.edu/medo/negative_findings.pdf, [10]). In order to tackle this issue we focused first on finding an acceptable definition for the class-level relation *canonically_has_part*, for which we had to introduce a canonicity predicate $C(p,t)$ ("p is a canonical anatomical structure at time t"). Finally the individual-level **lacks_part** relation emerges as definable in terms of **instance_of**, **part_of** and *canonically_has_part*. Aided by **lacks_part**, one could now easily construct a plethora

[3] Individual-level relations will be written in **boldfaced**, while class level in *italics*.

of related relations (e.g. **canonically_has_initial_part_one**, **canonically_has_at_least_one**, **lacks_function** etc.), and express many otherwise inaccessible truths (e.g. "My hands lack fingers, therefore I lack fingers").

Two related philosophical issues had to be tackled in connection with this relation: (i) **lacks_part** obviously connotes normality, a notoriously thorny philosophical challenge, hence in designing an acceptable definition care had to be taken so as to keep matters as generic as possible, thus avoiding overt commitment to a philosophical stance or other; (ii) RO was supposed to target, by design, a canonical state of affairs ("John **lacks_part** finger" is not, for example, a sentence expressible in the Foundational Model of Anatomy (FMA: http://sig.biostr.washington.edu/projects/fm/index.html)), hence **lacks_part**, and all the other associated relations are, *prima facie*, either unnecessary, or simply not to be included in RO.

Let p, q, f and g be variables that range over individual anatomical structures, t, t' range over time(s), P and F variables that range over anatomical structures universals. Let $C(p, t)$ stand for "p is a canonical anatomical structure at time t."

We submit the following definitions:

$$P\ \mathit{canonically\_has\_part}\ F \stackrel{\Delta}{=} \forall q \forall t' [q\ \mathbf{instance\_of}\ P\ \mathbf{at}\ t' \wedge C(q,t') \rightarrow \exists g (g\ \mathbf{instance\_of}\ F\ \mathbf{at}\ t' \wedge g\ \mathbf{part\_of}\ q\ \mathbf{at}\ t')]$$

$$P\ \mathit{canonically\_has\_part\_one}\ F \stackrel{\Delta}{=} \forall q \forall t' [q\ \mathbf{instance\_of}\ P\ \mathbf{at}\ t' \wedge C(q,t') \rightarrow \exists! g (g\ \mathbf{instance\_of}\ F\ \mathbf{at}\ t' \wedge g\ \mathbf{part\_of}\ q\ \mathbf{at}\ t')],$$

with ∃! defined in the usual manner:

$$\exists! x A(x) \stackrel{\Delta}{=} \exists x [A(x) \wedge \forall y (A(y) \rightarrow x = y)].$$

Informally this can be rendered as "*P canonically_has_part(_one) F* =df. all canonical instances of P have (at least) one part that is an instance of F;" e.g.: human *canonically_has_part(_one)* heart.

$$p\ \mathbf{lacks\_part}\ F\ \mathbf{at}\ t \stackrel{\Delta}{=} \overbrace{\exists P (p\ \mathbf{instance\_of}\ P\ \mathbf{at}\ t \wedge P\ \mathit{canonically\_has\_part}\ F)}^{*} \wedge \neg \exists f (f\ \mathbf{instance\_of}\ F\ \mathbf{at}\ t \wedge f\ \mathbf{part\_of}\ p)$$

The formula denoted here by * will be dubbed in the following the "canonicity clause." This reads, informally, as: "*p* **lacks_part** *F* =df. (there is a universal *P* such that *P canonically_has_part F* and *p* instantiates *P*) and (there is no instance of *F* that is part of *p*)];" e.g.: John **lacks_part** finger (N.B.: John lacks *all* fingers!).

We can also define:

$$F\ \mathit{canonical\_part\_of}\ P = \forall f \forall t [f\ \mathbf{instance\_of}\ F\ \mathbf{at}\ t \wedge C(f,t) \rightarrow \exists p (p\ \mathbf{instance\_of}\ P\ \mathbf{at}\ t \wedge f\ \mathbf{part\_of}\ p\ \mathbf{at}\ t)]$$

Informally: "*F canonical_part_of P* =df. any canonical instance of *F* is part of an instance of *P*;" e.g.: human heart *canonical_part_of* human.

As an immediate property one should obtain:

$$\exists F (p\ \mathbf{lacks\_part} F\ \mathbf{at}\ t) \rightarrow \neg C(p,t),$$

which says that if *p* lacks a part, then *p* cannot be canonical.

Nature Precedings : hdl:10101/npre.2008.2479.1 : Posted 5 Nov 2008

Another interesting (and also very intuitive) property: If (p lacks F at t & p part of p' at t) then p' lacks F at t. Formally:

$$p\ \mathbf{lacks}\ F\ \mathbf{at}\ t \wedge p\ \mathbf{part\_of}\ p'\ \mathbf{at}\ t \rightarrow p'\ \mathbf{lacks}\ F\ \mathbf{at}\ t\,.$$

(Think, for example, of "My hands lack fingers, therefore I lack fingers.")

Here are some other related definitions, more-or-less trivial and/or useful:

$$p\ \mathbf{has\_at\_least\_one}\ F\ \mathbf{at}\ t \stackrel{\Delta}{=} \exists f\left(f\ \mathbf{instance\_of}\ F\ \mathbf{at}\ t \wedge f\ \mathbf{part\_of}\ p\ \mathbf{at}\ t\right)$$

$$p\ \mathbf{has\_exactly\_one}\ F\ \mathbf{at}\ t \stackrel{\Delta}{=} \exists! f\left[f\ \mathbf{instance\_of}\ F\ \mathbf{at}\ t \wedge f\ \mathbf{part\_of}\ p\ \mathbf{at}\ t\right]$$

$$f\ \mathbf{initial\_part\_of}\ P \stackrel{\Delta}{=} \exists t \exists p \forall t'\left(t'\ \mathbf{earlier}\ t \rightarrow p\ \mathbf{instance\_of}\ P\ \mathbf{at}\ t' \wedge f\ \mathbf{part\_of}\ p\ \mathbf{at}\ t\right)$$

$$p\ \mathbf{has\_initial\_part}\ F \stackrel{\Delta}{=} \exists t \exists f \forall t'\left(t'\ \mathbf{earlier}\ t \rightarrow f\ \mathbf{instance\_of}\ F\ \mathbf{at}\ t' \wedge f\ \mathbf{part\_of}\ p\ \mathbf{at}\ t'\right)$$

The **initial_part** relation is primarily meant to address parthood in systems for which one can talk about a lifetime, as in, e.g., "John was born with (at least one) nipple." Note, however, that these definitions also allow for "John was born with (at least one) tail." We will be looking further for relations that prevent this.

One trivial variation on the **initial_part** relation is:

$$p\ \mathbf{has\_initial\_part\_one}\ F \stackrel{\Delta}{=} \exists t \exists! f \forall t'\left[t'\ \mathbf{earlier}\ t \rightarrow f\ \mathbf{instance\_of}\ F\ \mathbf{at}\ t' \wedge f\ \mathbf{part\_of}\ p\ \mathbf{at}\ t'\right]$$

Example: "John was born with one head." To exclude either of "John has at least one/has exactly one/was born with at least one/was born with exactly one tail," one would have to add the canonicity clause throughout (where appropriate); e.g.:

$$p\ \mathbf{canonically\_has\_at\_least\_one}\ F\ \mathbf{at}\ t \stackrel{\Delta}{=} * \wedge \exists f\left(f\ \mathbf{instance\_of}\ F\ \mathbf{at}\ t \wedge f\ \mathbf{part\_of}\ p\ \mathbf{at}\ t\right)$$

or

$$p\ \mathbf{canonically\_has\_initial\_part\_one}\ F \stackrel{\Delta}{=} * \wedge \exists t \exists! f \forall t'\left[t'\ \mathbf{earlier}\ t \rightarrow f\ \mathbf{instance\_of}\ F\ \mathbf{at}\ t' \wedge f\ \mathbf{part\_of}\ p\ \mathbf{at}\ t'\right],$$

etc.

For non-anatomical senses of "lacks" ("p lacks sense of smell," "p lacks sense of pain," "p lacks oxygen" etc.) one simply replaces the **part_of** and *canonically_has_part* relations in the above definition of p **lacks_part** F **at** t and P *canonically_has_part* F with the corresponding relations, just as suggested in [10]; e.g.:

$$p\ \mathbf{lacks\_function\_at}\ t \stackrel{\Delta}{=} \exists P\left(p\ \mathbf{instance\_of}\ P\ \mathbf{at}\ t \wedge \Phi(P)\right) \wedge \neg \exists f f\ \mathbf{function\_of}\ p\ \mathbf{at}\ t\,.$$

Here the monadic predicate $\Phi(P)$ stands for "P canonically has function" and is defined similarly to P *canonically_has_part* F:

$$\Phi(P) \stackrel{\Delta}{=} \forall q \forall t'\left[q\ \mathbf{instance\_of}\ P\ \mathbf{at}\ t' \wedge C(q,t') \rightarrow \exists g g\ \mathbf{function\_of}\ q\ \mathbf{at}\ t'\right].$$

It is not clear so far what are the relevant relations involved in "p lacks sense of smell," "p lacks sense of pain," "p lacks oxygen" etc., however, it is a good bet that

Nature Precedings : hdl:10101/npre.2008.2479.1 : Posted 5 Nov 2008

they will have to be based on different relations than those uncovered so far, just as *p* **lacks_function_at** *t* is based on **function_of** (see below for a treatment of "function").

2.2. connected_to

While some rudimentary topological relations are already included in RO, none of them can account for connectedness, which is a very important feature in Human Anatomy, among others. Two primitives were necessary in order to carry out the task of capturing connectedness as accurately as possible: a **closure_of** individual-level relation, and a *fiat boundary* predicate ($FB(x)$). These allowed us to construct two rival notions of connectedness, each with its advantages and drawbacks: (i) the first one follows rather closely standard set-theoretical topology (see [12], http://ontology.buffalo.edu/smith/articles/topo.html), by submitting the **closure_of** relation to Kuratowsly's closure axioms, and by defining most of the basic notions (border, boundary, interior etc.); one notable difference is that standard topology has been given here a mereological reading (think "objects" as "sets of atoms"). The interesting novelty is the definition of strong connectedness as the connectedness of the interior(s) ([12]); (ii) the second route to connectedness is based on the notions of *fiat* and *bona fide* boundaries, developed in [13] (http://ontology.buffalo.edu/smith/articles/fiatvs.pdf). Very briefly, two objects are considered connected if any partition of their mereological sum never yields pure *bona fide* boundaries, i.e., it always yields at least a patch of *fiat* boundary.

In more detail, and assuming the above notations, we start by assuming as primitives: (a) "*p* **closure_of** *q* **at** *t*" (which yields a function $p=c(q,t)$), and (b) the usual mereological functions: mereological sum ($x \cup y$), mereological complement ($\bar{x}$), mereological intersection ($x \cap y$) and mereological difference (x-y), governed by the corresponding axioms of mereology, plus the usual closure axioms (expansiveness, idempotence and, respectively, additivity):

$$x\ \mathbf{part\_of}\ c(x,t)\ \mathbf{at}\ t$$
$$c(c(x,t),t)\ \mathbf{part\_of}\ c(x,t)\ \mathbf{at}\ t$$
$$c(x \cup y,t) = c(x,t) \cup c(y,t).$$

We now define the notion of a boundary by means of a boundary function:

$$y\ \mathbf{boundary\_of}\ x\ \mathbf{at}\ t \stackrel{\Delta}{=} y = b(x,t),$$

where $b(x,t)$ is the boundary function:

$$b(x,t) \stackrel{\Delta}{=} c(\bar{x},t) \cap c(x,t).$$

We now have two ways of defining our target **connected_to** relation:

1. Define first the interior $i(x,t)=x-b(x,t)$ of an object. Further define "*p* **connected_to** *q* **at** *t*" as:

$$p\ \mathbf{connected\_to}\ q\ \mathbf{at}\ t = \forall z \forall y \left[i(p,t) \cup i(q,t) = y \cup z \rightarrow ** \right]$$

Nature Precedings : hdl:10101/npre.2008.2479.1 : Posted 5 Nov 2008

Nature Precedings : hdl:10101/npre.2008.2479.1 : Posted 5 Nov 2008

where ** is:

$$** = \exists w\left(w \textbf{ part\_of } z \textbf{ at } t \wedge w \textbf{ part\_of } c(y,t) \textbf{ at } t\right) \vee \exists w\left(w \textbf{ part\_of } y \textbf{ at } t \wedge w \textbf{ part\_of } c(z,t) \textbf{ at } t\right)$$

…meaning that two objects are connected if however we may split the mereological sum of their interiors into two parts *y* and *z*, then ** holds (i.e. either *z* overlaps with the closure of *y*, or *y* overlaps with the closure of *z*). This definition has been adapted from the *strong connectedness* definition introduced in Topological Foundations of Cognitive Science ([12]).

A less intuitively attractive (in our opinion) alternative way of defining the **connected_to** relation, [4] would be to switch in the above definition the mereological sum of the interiors, with the interior of the mereological sum, as in the following formula:

$$p \textbf{ connected\_to } q \textbf{ at } t = \forall z \forall y\left[i(p \cup q, t) = y \cup z \rightarrow **\right]$$

2. Introduce another primitive predicate, *FB*(*y*) meaning "*y* is a (patch of) *fiat boundary*." With this, *p* **connected_to *q* at** *t* becomes:

$$p \textbf{ connected\_to } q \textbf{ at } t = \forall z \forall y\left[p \cup q = z \cup y \rightarrow \exists b'\left(FB(y) \wedge b' \textbf{ part\_of } b(y,t) \textbf{ at } t\right)\right],$$

…meaning that any partition of the mereological sum of the two objects never yields pure *bona fide* boundaries, i.e., it always yields at least a patch of *fiat* boundary.

A few comments regarding these two major ways of capturing the intuitive notion of connectedness:

1. Both these two definitions are rather strong in that they not only imply that the two objects are connected, but that, moreover, each one in part is a connected object (so they are not "spread" in space, as it were). The definitions *can* be reformulated so as to yield weaker conditions, however, such a weaker definition doesn't *prima facie* seem to be of much interest in the field of biomedical ontologies (RO's initial target).
2. The first manner is closer to standard set-theoretic topology in defining most of the basic notions (closure, border etc.), the difference being mostly that standard topology has been given a mereological reading (think "objects" as "sets of atoms"). The interesting development/novelty remains the definition of strong connectedness as the connectedness of the interior(s). We are, at this point, not sure whether there are any interesting results in standard topology regarding strong connectedness. We are also having a hard time to think in topological terms of an instance of a connected set that is not strongly connected. As for the issue of *two* strongly connected sets, the following examples should shed some light:

   (0, 1) and [1, 2) are two disjoint, connected, but *not* strongly connected sets/intervals;

   (0, 1] and [1, 2) are two non-disjoint, connected, but *not* strongly connected sets/intervals;

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[4] see notes below containing some comparisons of connectedness with strong connectedness

(0, 2) and (1, 3) are two non-disjoint, connected, *and* strongly connected sets/intervals.

It would, finally, be interesting to know whether there are *dis*joint pairs of sets that are strongly connected.

3. The second definition is likely to be more successful and popular with circles of non-topologists, as the distinction between *fiat* and *bona fide* boundaries is sufficiently clear and intuitive. Some of the properties of the two types of boundaries have been formalized in [13]; nevertheless, even there, the distinction is assumed to be sufficiently clear from the get-go. One other reason why such a definition should be formulated in terms of *fiat/bona fide* is that connectedness in the realm of biology is supposed to capture essentially connected anatomical/biological structures, i.e., eventually, *molecular/atomic bonds*. Standard Euclidian topology certainly has very little to do with that. It would actually be very interesting to define a topology on $\mathbb{R}^3$ built explicitly onto such considerations.

2.3. inheres_in

Following the standard BFO practice, the individual-level inherence relation (**inheres_in**) is assumed as primitive. It is also postulated that its behaviour is (partly) governed, among others, by the well known "non-migration principle"—a staple of contemporary Aristotelian thinking. The class-level *inheres_in* relation follows swiftly from the individual-level version via some minimal logical maneuvering.

In detail, and assuming we allow for multiple inherence (one and the same continuant may inhere in another continuant at the same time), things can be envisaged in the following manner:

i. At the instance level one has the primitive "c_1 **inheres_in** c_2 **at** t" relation, satisfying the principle of non-migration (a **inheres_in** b **at** t & a **exists_at** t' → a **inheres_in** b **at** t') and possibly other axioms ("There are no bare particulars" (meaning, roughly, that there are no particulars without qualities) etc.);

ii. At the universal level we have the two definitions:

$$C_1 \ \textit{inheres\_in}\ C_2 \stackrel{\Delta}{=} (\forall c_1)(\forall t)\left[c_1 \ \textbf{instance\_of}\ C_1 \ \textbf{at}\ t \rightarrow (\exists c_2)\left(c_2 \ \textbf{instance\_of}\ C_2 \ \textbf{at}\ t \,\&\, c_1 \ \textbf{inheres\_in}\ c_2 \ \textbf{at}\ t\right)\right]$$

and

$$C_2 \ \textit{bearer\_of}\ C_1 \stackrel{\Delta}{=} (\forall c_2)(\forall t)\left[c_2 \ \textbf{instance\_of}\ C_2 \ \textbf{at}\ t \rightarrow (\exists c_1)\left(c_1 \ \textbf{instance\_of}\ C_1 \ \textbf{at}\ t \,\&\, c_1 \ \textbf{inheres\_in}\ c_2 \ \textbf{at}\ t\right)\right].$$

(c_1, c_2, are continuant instances, C_1, C_2 are continuant universals, t is a time instant.)

Nature Precedings : hdl:10101/npre.2008.2479.1 : Posted 5 Nov 2008

Nature Precedings : hdl:10101/npre.2008.2479.1 : Posted 5 Nov 2008

2.4. function_of

The initial version of RO included two main relations purportedly dealing with causality: *has_agent* and *has_participant*, from which several minor variations have been also obtained (*sometimes_participates_in*, *always_participates_in* etc.). It was suggested that any future endeavors to capture the notion of function in biology would have to employ these relations. While we do think these relations are indicative of causality, we have preferred a different route in order to achieve a comprehensive *formal* treatment of causality and function. In this respect we have adopted a stance that has proved immensely successful in the science of the second part of the 20th century—and in particular in applied science and engineering. Our motivation stems, in short, from the realization that biological organisms, and human organisms in particular, are paradigm examples of open *systems*. It is, hence, hardly surprising that an engineering treatment is perfectly suited to dealing with organisms, just as much as it is appropriate to dealing with machines and machineries. System(s) Theory[5] (aka Systemics), the brainchild of a biologist, not only offers the perfect environment in which causal chains can be encoded, but provides full-blown solutions to the type of problems encountered in the activity of constructing the function-causality side of a biomedical ontology. We, hence, see it as imperative to adopt system-theoretic and cybernetic terminology:[6] proceeding otherwise would amount, in fact, to rediscovering the wheel.

Before proceeding to the unfolding of a detailed ST-style account of functional/causal relations, here are some comments on, and considerations about the depth and type of RO ST infusion we are envisaging.

ST provides *sine qua non* tools for Engineering (Mechanical, Electrical/Electronics, Chemical etc.), also known as the "modular/systemic view/approach." Some of its most important abstractions (system/module, input, output, state, feedback) will be used in our account. While Engineering has benefitted enormously from ST, it has also proven immensely successful in Social Sciences as well. ST constitutes, in our opinion, the most natural tool for the study of interconnected modules/black boxes. Most of our considerations will hence adopt an input-output angle, very useful in the study of complex systems such as the human body.

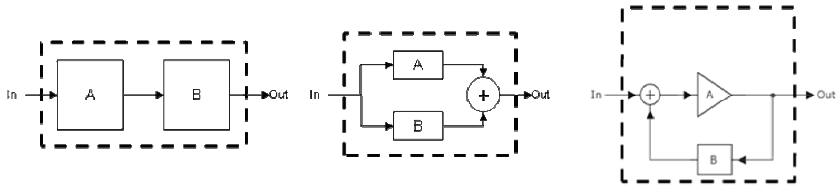

Figure 2: Interconnecting systems (serial, parallel, reaction (Cybernetics))

The parts that we will be using from ST have more to do with its mathematical projection (Dynamical Systems Theory), hence we will not employ notions like "holism," "synergy," "whole-ism," "emergence," which usually go with ST discourse. Nor will we be assessing aspects like *controlability, stability* etc., as they would exceed by far the scope of a simple RO enhancement. As a matter of fact (and this should

[5] ST for short.
[6] In what follows, Cybernetics will be regarded as a proper part of Systems Theory.

attenuate the fears of those wary of intrusions from pseudo-ST mythology), the level at which we'll be employing ST-notions is *little* more than skin deep; ST has been adhered to mostly for the sake of ensuring a minimal level of integration with all disciplines that use its highly interdisciplinary framework. As argued above, maintaining a connection with ST (be it minimal) will hopefully help us to avoid reinventing the wheel.

In brief, we have assumed the relations of **subfunction** and **section** of a function as primitives; using these and some other existing RO relations, we managed to define a host of new function and causality related individual-level relations such as **subsystem_of**, **function_of**, **has_function**, **has_output** etc. together with the corresponding class-level relations.

Without claiming to have solved some of the difficult (and genuine) philosophical issues surrounding the notion of a biological function, we do regard the infusion of system-theoretical terminology as our main contribution, and while we would have preferred that such system theoretic categories (system, subsystem, state evolution etc.) were included in BFO itself, including them in RO constitutes, in our opinion, the next best thing.

The paradigm examples of relations that have guided our modeling process (the so-called "use cases") are:

kidney *undergoes* excretion process
excretion process *has_participant* nephron
excretion function *implemented_by* kidney//kidney *implements* excretion function
kidney *has_output* urine//urine *output_of* kidney
kidney *has_input* blood // blood *input_of* kidney
excretion function *function_of* kidney//kidney *has_function* excretion function
filtration *subfunction_of* excretion function
nephron *subsystem_of* kidney *wrt* excretion function
excretion process *has_outcome* urine // urine *outcome_of* excretion process
excretion process *has_outcome* (clean) blood // (clean) blood *outcome_of* excretion process

One of the challenges that is likely to complicate the picture considerably is the fact that systems can have more than one function, and more than one output. As a solution we have adopted a vector view of functions, hence speak of *sections* (projections) of functions. Ultimately, we have modelled the analysis by taking set theoretical procedures as main inspiration. Let us consider, in this respect, the following case study:

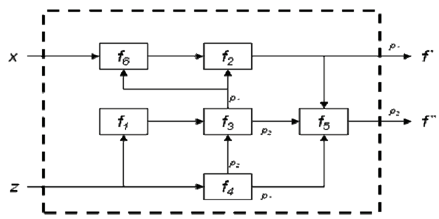

Figure 3: Complex system case study

Nature Precedings : hdl:10101/npre.2008.2479.1 : Posted 5 Nov 2008

If we construe each of the components of the big system (dotted line) as having a transfer function ($f_1, \ldots f_6$) that turns its input into an output,[7] and if we employ simple set theoretical operations (Cartesian product, composition and projection), we obtain for the big system a transfer function expressed by the following formula:

$$f(x,z) = \left(f'(x,z), f''(x,z)\right) = \left(p_1 \circ f, p_2 \circ f\right)(x,z),$$

which is actually a pair of functions (a vector), where

$$f' = p_1 \circ f = f_2 \circ \left\{ f_6 \circ \left[1_x \times p_1 \circ f_3 \circ \left(f_1 \times p_2 \circ f_4 \right) \right] \times p_1 \circ f_3 \circ \left(f_1 \times p_2 \circ f_4 \right) \right\},$$

and

$$f'' = p_2 \circ f = f_5 \circ \left[f' \times p_2 \circ f_3 \circ \left(f_1 \times p_2 \circ f_4 \right) \times p_1 \circ f_4 \right].$$

f, hence, has two sections, *f'* and *f''*. Note that f_5 is a subfunction of *f''* but not of *f'* (i.e. appears in *f''*'s functional decomposition but not in *f'*'s). We say that the system whose transfer function is f_5 has no causal contribution to the *f'* output. To adopt the terminology used in the paradigm examples: "*S_5 subsystem_of S wrt f''* is true," while "*S_5 subsystem_of S wrt f'* is not true." We have, hence, tried to follow such procedures in proposing and analyzing new relations, hoping that our relations turn out to be useful.

In the following, we will be adopting the following variable notations: *c, c', s, s', s''* range over continuant instances, *f, f', f''* over function instances, *p, p'* over process instances, *t, t', t''* range over instants of time, *T* over temporal interval individuals.

A first definition is: *f* **function_of** *c* =df. $\exists t$ *f* **inheres_in** *c* **at** *t*, which simply says that if a function (ever) inheres in a continuant, then the continuant has that function. Far from elucidating the (presumably) difficult notion of function as vehiculated in philosophical circles, it should allow us to get the whole functional edifice off the ground. Its reciprocal (*c* **has_function** *f*) has the same definition.

The following batch of relations should be taken as primitives. We trust, for now, that they are self explanatory, especially given the examples and case study above.

f' **subfunction_of** *f* (primitive)
f **has_subfunction** *f'* (primitive)
f' **section_of** *f* (primitive)
f **has_section** *f'* (primitive)
s **has_input** *c* **during** *T* (primitive)
c **input_of** *s* **during** *T* (primitive)
s **has_output** *c* **during** *T* (primitive)
c **output_of** *s* **during** *T* (primitive)

Use cases for some of the above:

this kidney **has_output** this urine sample **during** this time interval

[7] This, as a matter of fact, is not a perfectly general situation, as systems do not necessarily have a transfer function. For illustration purposes, however, this should do.

Nature Precedings : hdl:10101/npre.2008.2479.1 : Posted 5 Nov 2008

this electrical impulse **output_of** this nerve **during** this time interval
eliminate urine *section_of* excretion function
blood cleaning *section_of* excretion function

Note that both **has_input** and **has_output** have hitherto been designated as primitives, which is different from what one would have expected in view of our set theoretic inspiration. According to a set theoretical construal, given the input and the (transfer) function, one should be able to derive the output as the result of applying the function to the input. We have chosen not to reflect this in the general case, hence concede that the mathematical notion of function might not capture other meanings of the term (Biology, Philosophy etc.), where the "applying a function to an input" might be regarded as nonsensical.

Other defined relations, bearing in mind the above primitives:

c **undergoes** *p* =df. *t'* **first_instant** *p* & *t"* **last_instant** *p* → (∀*t*) [*t'* **earlier** *t* & *t* **earlier** *t"* → *p* **has_participant** *c* **at** *t* & (∀*c'*) (*p* **has_participant** *c'* → *c'* **subsystem_of** *c* **at** *t*)]; comment: for the duration of the process, *c* is the biggest system that participates in the process.

s' **subsystem_of** *s* **at** *t* =df. *s'* **part_of** *s* **at** *t* & (∀*f*) [*s* **has_function** *f* → (∃*f'*) *s'* **has_function** *f'* & *f'* **subfunction_of** *f*]; comments:" (a) the part's functions are always subfunctions of the whole's functions; (b) the dychotomy continuant/part_of and system/subsystem is meant to address calls for a *functional* (as opposed to "traditional") anatomy (see [14]); (c) "subsystem" emerges as a restriction/child of **part_of**, wherby some continuant **part_of** some other continuant is a subsystem just in case it is not functionally/causally inert in whatever processes the encompassing continuant undergoes. The human vermiform appendix could be seen as a counterexample at this point, as a part of the canonical human body that is devoid of function (presumably vestigial).

s' **subsystem_of** *s* **wrt** *f* **at** *t* =df. *s'* **part_of** *s* **at** *t* & *s* **has_function** *f* → (∃*f'*) *s'* **has_function** *f'* & *f'* **subfunction_of** *f*. Comment: while in the previous relation the part was involved in *all* of the whole's functions, this relation captures the contribution of a part with respect to a *section* of the whole's function; example: the kidney implements the excretion function, however, the kidney's main "functional unit" (the nephron) has no role in the kidney's endocrine function.

p **has_outcome** *c* =df. (∃*s*) [*s* **undergoes** *p* & *t'* **first_instant** *p* & *t"* **last_instant** *p* → *s* **has_output** *c* **during** (*t',t"*)]; The reciprocal, *c* **outcome_of** *p*, would have the same definition. Comment: process *p* has continuant *c* as outcome if the system that undergoes the process has continuant *c* as output; e.g.: this breathing process **has_outcome** this volume of CO_2.

f **realized_by** *p* =df. (∃*s*) (*s* **undergoes** *p* & *s* **has_function** *f*); *p* **realizes** *f* has the same definition. Natural language rendering: a function is realized by a process if it is implemented by a system that undergoes the process in question; e.g.: excretion process *realizes* excretion function.

Nature Precedings : hdl:10101/npre.2008.2479.1 : Posted 5 Nov 2008

Nature Precedings : hdl:10101/npre.2008.2479.1 : Posted 5 Nov 2008

3. Open Issues, and Future Work

Aside from supplying the universal-level correspondents of the above individual-level relations, we regard as imperative the tackling of the following two major technical issues:

1. As things have been canvassed so far, it should make sense to proceed at splitting the outputs of a system according to the function sections, that is, it should make sense to talk about vector-style outputs: e.g. "kidney *has_output* (urine, blood)." The picture, however, has become very complicated. While vector-style functions might be easier to swallow, RO target users (medical informaticians and, eventually, clinical practitioners) might be put off by the increasingly complicated panorama of relations. What started off as an attempt to put forward a list of simple relations to be used as a first step towards computer-friendly medicine, has quickly escalated in complexity. The answer to this, we think, should be looked for in the complex nature of medical reality, and of reality in general.
2. The matter of specifying/individuating (sub)systems other than by simply giving their function (i.e. by saying "the (sub)system" that does this or that) is, we think, very cumbersome. To rephrase, say *s* is a system having function *f*, and *f'* is a subfunction of *f*. *Is there such a thing as a subsystem s' of s that implements or that has_function f'?* If anything, this looks to be an issue regarding the expressive power of two languages: the functional language versus the structural one. To what extent are these comparable, or even interchangeable?

4. Concluding Remarks

A commonly held opinion among computer scientists and software engineers is that ontologies need to be more expressive. Enhancing their expressiveness can be done by providing them with means to capture many other relations, aside from the primordial ontological one (the *is_a* taxonomy). Some of these new additions have been dealt with extensively above, some (the more basic ones) in the initial RO paper ([9]). The most widespread computing tools used to represent ontologies in electronic format, OWL and its Protégé GUI (http://protege.stanford.edu/), certainly allow for such additions (recall the "Properties" tab in Protégé). However, by submitting to such demands from the community of ontology users, ontologies have overstepped their historic authority. They have effectively turned into *theories*, namely theories in .owl clothing. While we certainly do not find this as distressing in the slightest bit, we also find worth remarking that efforts aimed at regimenting scientific theories in the framework of FOL are far from new.[8] We would hence like to conclude by giving credit to a entire tradition in 20th century Philosophy of Science, and to express our hopes that the recent resurgence of .owl ontologies, and the assimilation of ontology development to a KR style, will lead to a better understanding and greater appreciation for a tradition frequently regarded as having little (or nothing) to do with concrete computational targets, but more with the esoteric part of man's spiritual creations.

[8] See, e.g., [15].

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