A two-sorted logic for structurally modeling systems

H.T. Goranson\textsuperscript{a},*, Beth Cardier\textsuperscript{b}

\textsuperscript{a} Sirius-Beta, Inc, Virginia Beach, VA, United States
\textsuperscript{b} The University of Melbourne, Melbourne, Australia

\textbf{A B S T R A C T}

Structural modeling of complex biological systems relies on formalisms inherited from physics. These formalisms scale poorly when dealing with interactions among many variables and agents working in systems that cohere at multiple layers. We propose a two sorted logic that supplements existing formalisms to mitigate these problems. The purpose of this second logic is to track how multiple contexts relate to each other, as well as to the dependent structures they inform: a situating of situations. In this way, we aim to capture the multi-layered and multi-system dynamics that have been elusive in modeling emergent systems. An apoptosis example is explored in the context of mental concepts.

\textsuperscript{*} Corresponding author.
\textit{E-mail address: tedg@sirius-beta.com} (H.T. Goranson).

0079-6107/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.

http://dx.doi.org/10.1016/j.pbiomolbio.2013.03.015
1. Introduction

The formalisms used in biology grew from the great insights in physics as applied in the physics of chemistry. The abstractions from physics have convenient practical advantages in supporting computational models; nearly all the basic abstractions are physically-based or intuitively accessible. These abstractions are effectively the formalisms that empower our reasoning and computation in all the sciences; in particular, they are used for both human and machine reasoning over biological phenomena.

What phenomena are these abstractions best suited for? Those that can be represented well as objects with influence. Over time, biology adopted this abstraction paradigm — with dependent abstractions such as fields and forces. They are so prevalent that in practice these convenient abstractions have come to be conflated with reality.1

In models based on these abstractions, systems are understood as compositions of interacting objects. Computational methods have evolved in support, so they predominantly also emphasize objects and their behavior. Because computers can handle massive numbers of objects and explicit interactions, systems — and especially biological systems — are now almost universally conceived as aggregations of their atomic components.2

Optimists in the field of computation and automated reasoning point to the growing ability of our computing machinery — the often misunderstood ‘Moore’s Law’ — to handle ever larger masses of these objects and relationships. This assumes that the solution to any problem in biology is no more than a matter of characterizing the basic objects and interactions and scaling the computing infrastructure.

There surely is some future in this approach, but there is also the haunting reality that as we better understand biological systems,

1 The notion of objects with properties and behavior has even colored most interpretations of quantum mechanics. We will make a brief remark on the limitations this carries in the section on influences.

2 In this statement we overlook the many techniques that exist to encapsulate atomic behavior in hierarchical layers. As the paper develops, we assume the reader will recognize these encapsulations as simple extensions of the basic abstraction philosophy of atomic aggregation. Some of them are described in later sections in the paper.
concepts at a psychological layer. The example complicates the inclusion of concepts further by connecting these to emotions, which we consider as urges — perhaps primitive — that shape the concepts that emerge in particular psychological states.

We believe that the example makes our stance on reductionism clear. We accept some reductionist mechanisms because they are obvious and useful. However, we avoid the need for building a paradigm on atomic primitives by adding model mechanisms decoupled from primitives.

The example is intended to be a convincing illustration only; our claim is that the method we propose can be generalized to any problem that spans such layers of and provides a formal anchoring for general computing.

The paper therefore is divided into the following sections:

- An introduction to some example biology (that of cell death) and some known difficulties in this field in Section 2.
- A brief survey of some fundamental modeling concepts as applied to the example, with a focus on logic in Section 3.
- In Section 4 we give some details of the example problem, followed by the example itself.
- Section 5 sketches influences that shaped the approach.
- A brief discussion of the framework compared to others related to ‘Biomathics’ follows in Section 6.
- Section 7 is a discussion of the applicability of the framework to the goals of ‘Biomathics’.
- Section 8 provides some suggested research ‘next steps’.
- Conclusions are given in Section 9, with an emphasis on the theme of the special issue.

2. Apoptosis: an example problem

Apoptosis — sometimes called programmed cell death — is a process that occurs in all animals and nowhere else. It is the complex sequence of events where cells die as part of the functioning of a healthy system. These are either replaced by new, similar cells or new differing cells or proteins in response to a need. In all cases, the death of the cell sends signals that trigger other processes. This phenomenon has been relatively well-characterized in the molecular domain at a local layer, and yet the system-layer imperatives are poorly understood.

This paper does not report new biological results; the example is chosen because the general concept is widely known, is involved in many essential processes and is implicated in many different types of disease. Many of its details have been mapped at a molecular layer. Researchers suspect that gaining a new perspective on this process will be a major step toward controlling cancer, autoimmune and age-related diseases.

Cells do die in a healthy body — many of them every day. The specific mechanisms of death are comparatively well understood at the cellular layer, once that death has been triggered. Researchers know the nature of the signals involved in the triggering of apoptosis, and in many cases they also know the exact sequence of molecular and cell interactions. Some good surveys have also been made regarding the nature of the signals for those processes.

That is the good news; moreover at this cellular layer, our existing abstractions and methods are capable of being as exhaustive as necessary.

The moderately bad news is that there are a bewildering array of cell types and systems to which these cells belong. Typically a cell contributes to multiple systems. (Stem cells have an extreme spread in this regard.) Brain and nerve cells can obviously affect systems by remote influence. But even ordinary cells, like a representative liver cell, contributes to several processes generally considered as systems, such as those supporting immunity, digestion and circulation. Human endurance and alertness — possibly aging — are related as well.

A cell dies under apoptosis when a certain enzyme (specifically a type of protease called a caspase) is released. These enzymes are stored in the living cell, bound until waiting for a signal. Once receiving that signal, their unbound presence in the system causes a cascade of steps to occur. We know of two primary pathways for turning executioner caspases loose in the cell. One is: the signal is received, and a set of related proteins (BCL-2) are affected. These control the health of the mitochondrial outer membrane within the cell. (Pro-apoptotic BCL-2s are in balance with anti-apoptotic BCL-2s, regulated by a third variety of BCL-2s.) The signal shifts the balance, allowing the membrane to become permeable. (Mitochondria are components of a cell that provide a wide range of functions, including supplying energy and regulating growth.)

Soluble proteins, including cytochrome c, then pass through the mitochondrial membrane from the mitochondria and dissolve in the fluid (cytosol) in the cell. Here, it combines with an adapter protein to form clusters (a process called oligomerization).

These clusters bind to the ends of initiator caspases. The initiator caspases release executioner caspases that then proceed as ‘cutting machines’ to disassemble the cell in a way that provides both signals and raw material for the next steps. There are other ways to trigger these caspases (infection, cell stress, DNA influence...) and sometimes the triggering processes intermingle.

In a typical human, this happens about a million times a second. The exact steps of this entire cycle are fairly well mapped at the cell layer for a variety of animals.

Unfortunately, the incoming, outgoing and intermediate control signals are part of finely tuned system-layer mechanisms. Researchers just don’t understand those mechanisms in ways other than simply adding more steps at this cellular layer.

For example, we can say in English that the function of a liver is to support digestion, detoxify, produce vital proteins and regulate metabolism. But there is no formal framework for modeling the interaction among these functions at this high level, much less a way to integrate the models of these functions with the detailed models of dynamics at the molecular-cellular layer. Our only option is to correlate measurements at the system level, and drill down to the molecular layer to trace details.

Even at the molecular layer, there may be problems, and we will mention some of those later. But a key theme of our work is that we do not question current molecular models as they are, or as they might be improved in the future. We supply a metastructure that subsumes and supplements these models.

There are models that capture molecular dynamics as differential equations (Aldridge et al., 2006), with every event represented as a signal (Lones et al., 2012) or by other models using metaphor...
But among the various options, our example uses the default abstractions (those used in the field) because our interest is in preserving contextual information and transferring it accurately. We also explicitly aim to capture cause — in this case, its effect at the molecular layer.

Field science is about measurement but theoretical science at its best is about understanding cause. Following general practice, we refer to a movie-like sequence of states — each state formally expressed as a fact (which is a collection of facts) and each state connected to another by connectives that potentially indicate cause.

Diagrammatically, we can represent the known steps in the process as causal events: the effect of one step causing another. This notion of cause is essential to practical understanding because by segmenting things so, we can imagine and engineer agents that replicate, block or modify by similar cause. By inserting a slot for causal agents, we begin to frame existing models in terms our approach can manage.

As it happens, while sequence is easy, causal mechanisms are notoriously difficult to pin down. In causal philosophy, the viability of causal reasoning has been debated since Hume (Hume, 2001), with theorists questioning how causal factors can be objectively identified and represented when the system is changing, and the model not intrinsically linked to nature. We entail these issues by positing causal reasoning as a matter of perceptive stance (Einhorn and Hogarth, 1983; Mackie, 1995), where the overlap of multiple contexts produces insight into potential causes (Cardier, 2012).

Local cause is still a matter of identifying the immediate signals, but the insights we need come from a contextual, distributed framework which will be described in a moment.

A dramatic local process in cell death is the guillotine effect enacted by free caspases. It is therefore tempting to assign causal agency to local events; that is, a protein encounters another, and causes a change.

But one could also observe that the cause was the high level need for the system to renew, or to respond to a threat. Or perhaps the cause was a deviant construction in the cell or gene, only now becoming relevant. As Einhorn and Hogarth argue in relation to causal determinations of agency, the attribution of cause changes depending on the context. This means that any useful understanding of a complex process such as apoptosis, which draws on and effects multiple systems, also requires a model that captures causal behavior from many perspectives, many levels.

2.1. Apoptosis in the olfactory receptor neurons

Consider now our detailed example, apoptosis in the olfactory receptor neurons. This cell death occurs in the nerves that sense smells, perform some pattern recognition and connect that information to the brain. The figure shows the basic arrangement of the key components.

There are many attributes in this example that make it difficult to model by exclusively low-level means. The 2004 Nobel Prize in Medicine was awarded for discoveries related to the organization of the olfactory system.
Neurons are a signal made tangible. Receptor neurons, like other neurons, communicate with each other by chemical and electrical means, acting to build and recall patterns. In many ways, they are more complex than other cell types (in our emergent systems context) because their purpose is to signal.

Olfactory neurons are an interface between inside and outside. The receptor neurons are the only neurons in the body exposed to the external environment.

The residue of cell death becomes collective memory. Olfactory neurons die and regenerate. The new ones are re integrated into the neural fabric as part of the maintenance of memory. This is unique among neurons outside of the hippocampus.

The system is aggressively dynamic, and evolves. Each neuron is short-lived — on the order of months — which means that this sense and its memory is quite a dynamic system. The physical array of sensors adapts over time to be more attuned to certain scents.

The example is consciously experienced. A cell of any system might be considered to be part of the information flow and memory of a system, but this is easier to envision in a system of cells whose flow and memory we actually experience. Generally speaking, every recognized smell enters conscious thought. An average human can name about 10,000 distinct scents and discriminate among 400,000.

Olfactory processing affects multiple conscious areas of experience. The sense of smell has a built-in synesthesia, because most of what we experience as taste is actually determined by the much more sensitive smell sensors, via olfactory receptor neurons.

Olfactory processing spans primitive and advanced developmental processes. The sense of smell is — in evolutionary terms — our most primitive, originating in how simple organisms respond to their environment. The receptors are thus functioning in an ‘emerged capability’ of how cells receive signals.

Olfactory processing spans physical and emotional processes. Smell memories are deeply associated with emotional situations, and smell can significantly affect associations. This latter quality is a focus in our example.

It is directly connected. Smell is the only sense that is not moderated by the thalamus, instead connecting directly to higher brain centers that play a role in our example.

These processes are biologically and emotionally urgent. Smell is an important component in sexual attraction. Smell memories are generally associated with internal story structures in the mind. All of this is to say that we can place the apoptotic behavior in a variety of overlapping contexts: chemical, pattern building, cognitive and emotional. How do we reason about the cell and molecular chain of events in these contexts?

2.2. Some interesting properties of the example

We have noted that the human olfactory system is remarkable. It utterly depends on breathing, a completely different bodily function. Possibly, an initial gasp when startled and increased breathing under stress are ways of increasing the ability to evaluate threats via scent.

When under stress, the body emits a scent that others can discern.

Among the senses, it is the one that puts its sensors in the most dangerous situations. Many particles and molecules that enter the nasal cavity are toxic, so it makes evolutionary sense for the neuron-sensors to be easily replaced, and for the replacement process to add to the memory profile.

The olfactory system appears to be more capable of directly triggering an immune response than any of the body’s systems outside the bloodstream. In particular, the actions of the human leukocyte antigen are known to be influenced by signals from the olfactory system. The antigens manufacture T-cells that are unique to the specific pathogen and often unique to each human.

As the oldest evolved sense, it is directly connected (in part) to the similarly oldest parts of the brain.

Our example will focus on the layer of biophysics where scents are captured and memories built at the neuronal layer, together with emotional concepts related to sex, love and concepts of self. A general reference for the olfactory system is (DeMaria and Ngai, 2010), and for apoptosis is (Green and Reed, 2011).

3. A critical modeling problem: multisystems with ephemeral cause

As mentioned, the difficulty of modeling problems in complex biological systems spans many ailments that urgently require fresh approaches.

In 2010, the 25th conference on AIDS research at the US National Institute of Health produced a progress report. Three billion dollars per year was being spent on AIDS by NIH, part of many billions spent worldwide in the previous quarter century. The main strategy during that time was an investment in structural biology, then managed under the Protein Structure Initiative.

The goal was to make massive progress in discovering the structure (read: shape) of the molecular components and trace the interaction of those components as processes progress in healthy and diseased bodies. It was a heavy investment in what we have been calling physics-based abstractions. The rationale was inspired by the genome project, also a structure-based mapping problem. A similar ethic was behind the investment in protein structure; the work on structure is both an extension of this idea and an extension of gene-related processes. AIDS funding is only one of the sources for this work.

Massive progress was made in those 25 years, with those NIH billions combined with similar focused work from other programs and nations. The purpose of the yearly conference was to share that progress. The director relayed the good news in the progress of this survey. But he then remarked that this level of detail was not sufficient for a breakthrough and indeed perhaps an opportunity had been lost with this approach (Cassman, 2011). In discussion at the meeting, and privately with others, it was clear that some in the community see structural mapping as important, even essential, but not sufficient.

There is no lack of funding for AIDS research. And there is no lack of intelligence in the scientists; these are the best of the best. Something is missing. We suggest that the problem is the lack of some fundamental tools which would enable a workable model of lower and higher level systems operating together. Part of the problem is that the abstractions of physics, though ideal for molecular structure and dynamics, are poorly suited for modeling what we will call here emergent system dynamics.8

8 Our expertise in this comes from a general problem in reasoning about multiple coherent contexts in automated systems. Just as biology is limited by abstractions of molecules with causal chains, so too are today’s computers limited by abstractions of facts with logical chains. We suppose insights from the general problem apply to reasoning over emergent living systems.
3.1. The limits of a one-sorted logic

In the emergent dynamics of biological systems, multiple forms operate at a variety of layers, with an integrated coherence that is difficult to grasp. Even if this could be captured using current methods, we cannot wait for the structural biologists to exhaustively map every molecular object and dynamic and then attempt to assemble a big picture; we must reason about these systems with incomplete knowledge, though one of the goals of our agenda is to clarify what is missing at the molecular layer.

A mathematical logician would characterize this as a one-sorted logic problem. The logic of the system is determined by its basic abstractions and their connectives. In this case, that logic is based on the abstractions and connectives of physics. Viewing that logic through the lens of categories (or some other lens, for example non-monotonic structures) still gives you the same logic. What we need is a second logic, one that is a logic of multiple systems.

A promising approach to capturing these higher-level behaviors is to rely on categoric abstractions (MacLane, 1971). This makes great sense, because:

- The fundamental abstractions in category theory are structures of systems regardless of the specific details of the population of any system.
- We have well understood formalisms for translating from the mathematics of objects (in set theory) to the mathematics of systems (in category and group theories) (Sørensen and Urzyczyn, 2006). Objects in this context are molecular structures.
- We also have a good (good enough) understanding of how categoric structures inform analysis of relevant computations, even to the extent of identifying system-specific functions.

Examples of using categories in biology abound, with different flavors producing different advantages. Some of these are described below in Section 6, 'The Approach Compared to Others.' A basic problem, however, is that these categoric abstractions are derivative; that is, they are extracted from abstractions and models in which objects and forces are primary. The solutions they offer in these cases are simply a different lens into the model constructed using the initial formalisms. (The motive in such work is that translation into categories reveals structure of the system in such a way that it can be better analyzed and thus reveal otherwise hidden dynamics of the original system.)

The problem with this is intuitively clear: if you approach the world as collections of objects with forces producing fields; and you create logical (i.e., set theoretic) models — namely, the common models of scientific engineering — and if you subsequently abstract system views in category theory, then you have inherited all the limitations of the initial reductionist view.

Said another way, the power of category theory to provide insight into system dynamics is neutered if you are simply translating the original model. The effect is that the molecular biologist can be modeling with large blind spots, even with sophisticated application of categories.

3.2. A two-sorted logic

Our approach uses a two-sorted logic. We reason using statements that resemble equations, with a left hand side (LHS) and right hand side (RHS). They are related by the turnstile symbol (\(\vdash\)). In a two-sorted expression such as this, the facts as represented on the RHS are supported in or by the situation on the left. On the RHS are individual facts; on the LHS are contexts, which we refer to as 'situations.'

As per Barwise and Perry (1983) and Devlin (1995), facts are represented as infons.

A rudimentary infon construction of the facts from Fig. 3 is shown in Fig. 5.

Before exploring the complex biological example, here is a simple case that shows how the LHS and RHS demonstrate relations of context. Below, a series of facts about a car is expressed on the RHS. These can support the situation of your car, or the different
situation of my car, or a composite situation of several cars, on the LHS Fig. 4.

Now [My car and yours] \(\Rightarrow\) < Has four wheels > and < Has four doors >

Generally, the RHS is used for anything we can describe in the usual way. Its format is particularly friendly to the kinds of details that appear in object-centric, molecular biological models. Anything known can be recorded on the RHS, including things that can be named that are not known. An example of the latter may be that we know that olfactory receptor neurons have a different distribution of apoptotic oligomer foldings (the clusters that when formed are part of the trigger chain) than usual but we don’t know that distribution yet — or how it correlates with initial sense memory.

In other words, anything that can be done without our proposed framework is placed (by us) on the RHS. Together with nearly everyone, we expect better tools and methods to appear for RHS dynamics. Some of these are described below, in Section 6, ‘The Approach Compared to Others.’ Our novelty is in adding the LHS, and the second sort of ‘logic.’

For now, consider the LHS to be a denotation of the situation (context) in which the RHS is true. For instance if I were reasoning about your sleeping habits, I might be able to list a number of behaviors and attitudes. These would be RHS statements.

But when I refer to you as a whole being, in my mind I have a placeholder for that more complex, less qualifiable entity. There are many facts about you that I don’t know and that no reasonable person could. I surely would never know subtle things, such as how you think you appear in your partner’s dreams.

And yet, with all these unknowns and unknowables, it is common for people to reason about each other as whole beings. Following Devlin (Devlin, 1998) (and others), we would call this a soft object. The reasoning we perform about such soft objects — entities that depend on implicit knowledge — is soft reasoning. That means that from time to time, a LHS object appears on the RHS as a placeholder. An example would be: in the situation of this example (our LHS situation), we state that you assume your bedmate has some subconscious associations about your smell (the soft object previously on the LHS) but we know we don’t know what they are.

Now [Your bedmate’s mind] \(\Rightarrow\) < Attracted to you > and < Likes your smell >

Maybe [Your bedmate’s mind] \(\Rightarrow\) < Attracted to you > because

\(\langle\text{Now} [\text{Your bedmate’s mind}] \text{ Likes your smell}\rangle\)

The first expression says: your sexual partner likes your natural smell.

The second expression says: your sexual partner is attracted to you because they think they like your natural smell. Note that the last infon has a situation as an element.

Here is another example of the two kinds of information that can be captured by a two-sortied logic, this time straddling the soft domain of story, and the formal representations of chemistry. Suppose you were a beer brewer, and knew a lot about the chemical properties that create foam, alcohol and a spectrum of smells. Also, suppose you independently knew what visual, olfactory and texture sensations were related to desirable beer in your target market.

You could reason about the emotions of marketing slogans and process chemistry in the same logic. People do this. But it might make more sense to use chemistry and physics for what they are good for, and something like intuition on a LHS for what it is good for. Here is an example in which two different kinds of beer are associated with two different marketing images:

\(\text{Sexy[Beer Story]} \Rightarrow\) < Process 14 > and < Hops 22 > and...

\(\text{Many[Beer Story]} \Rightarrow\) < Process 6 > and < Hops 21 > and...

In this case, if we had a means of reasoning on the LHS, you would be able to work toward just the right impression of smells for your market, say combining many and sexy. Because there is a connection with the RHS, you may — if you design the system well — be able to automatically find the corresponding RHS process plan to manufacture a beer with the desired impressions.

The analog in our example domain may involve reasoning about stored emotion-driven concepts, the mechanics of apoptosis and different mechanics of scent perception. A goal would be to indicate the nature of signal flows in the olfactory system.

The basics of our proposal are:

- The relationship between RHS and LHS allows us to ‘reason’ on either side and gain insight into the other.
- We use RHS methods to express information from the model that a practitioner prefers in his/her domain.
- We introduce the notion of a soft item as a LHS ‘situation.’ This can be a circumstance where everything is exhaustively known, but usually there are unknowns. These unknowns can be of different types: tacit knowledge, facts that can be made explicit but for some reason (often cost) are implicit or even facts that might not be knowable.
- RHS expressions always have a governing logic that is formally representable, which in practice means that RHS expressions are set theoretic.

The model of soft items, which is unique to our approach, has a few notable qualities:

- We can form turnstile expressions (LHS \(\Rightarrow\) RHS) which allows facts to be associated with a soft situation, or vice versa.
- We can place such a soft situation in a RHS expression, as already noted. In doing so, we might ‘zoom’ into the item (using known facts) as part of a logical reasoning process and end up with all facts on the RHS.
- LHS objects are represented as categories. These can be categories distinct from the categories that can be directly extracted from RHS expressions. On the RHS they represent another lens into those expressions.
- To keep the LHS/RHS relationships clean, we impose some constraints on the expression of facts and connectives on the RHS, using ‘infs’. These are expressive conventions only: any consistent reasoning system would be mappable to our RHS structures.
- Relationships among LHS categories are managed by operations native to category theory.\(^{11}\) We use certain mathematics to define these categories, their relationship to RHS expressions and their relationships one to another. This latter set of relationships forms a coherent universe of relationships that we define as our second sort of logic.
- The dynamics on the LHS — the instances of the categoric logic — are based on a framework developed by Cardier (2012) regarding causal agency in stories. These LHS dynamics are designed to track the situating of situations. This is a key feature

\(^{11}\) Such relations in category theory are morphisms, and we often express these as functors. Functors help us map to computable functions in programming code.
of our approach: it is not enough to reason in one context. In order to capture the behavior of emergent systems, we reason about the way multiple contexts interact with and influence each other. A key behavior is Governance, which we will refer to later. These higher level dynamics then impact on, and are informed by, others.

- The dynamics on the LHS are progressively refined by theory and test just as they are in any scientific endeavor. For any domain, the laws of particular situations will also be devised, to enhance our general multi-situational dynamics. Thus, the building of the dynamics is also emergent, as we: extract patterns from observed behavior; extract patterns from the abstractions and models; predict future behavior from the theory; then test and adjust them.

3.3. Introducing infons

We have two kinds of notation for infons. The first is informal, and you have already seen it in Fig. 5. It uses ordinary English phrases for the objects under consideration. These expressions are denoted by brackets on the LHS and single chevrons on the RHS.

In the example regarding your bedmate’s opinion of your scent, the term ‘because’ is a logical connective. Below we show a more active connective; ‘and,’ that captures cause.

Now [My mind] = < Now [Your bedmate’s mind] Likes your smell > and so < You shower infrequently >

This expression says: my current opinion is that you don’t shower as often as you might because your sexual partner likes your natural smell.

A second kind of notation is more structured. In this case, the RHS uses double chevrons to denote that we have structured facts in a way that we can formally integrate into a two-sorted framework. Here is where we introduce some constraints into the way the RHS is structured.

A human fact: “Mary dreams of a dinner” would be represented in a packet that extends the convention set by Devlin as an infon (Devlin, 1995). Our infons have one internal relation which we modify them to be correct in the context. The second operation of the ontological dependencies of the (front part of the) infon to change its interpretation.

The expression below has the natural language notation at the top and the more formal one under:

< Mary dreams of dinner >
< dream : Mary, dinner; < >

We use sans-serif fonts for elements native to the RHS. Proper nouns are capitalized. You will note that the infon is governed by its relation, in this case ‘dream’ so that is in italics. The following two words are the parameters of the relationship. For computational efficiency, we always use binary relationships.12

The character after the semicolon, <, is explained later; it is a function defined by the situation on the left that qualifies the infon.13 Here, the situation is the present, so the relation ‘dream’ in the example above is qualified to the present tense. In general, it can color the infon in many different ways.

In our apoptosis sequence, “the active caspase recruits a populated oligomer,” an infon may be expressed as:

< recruit : active caspase, populated oligomer; < >>

Note the way that the agency concept ‘recruit’ is shifted to the front of the infon, while the < is placed at the end.

In nominal situation theory which is a precursor to our work, the < function is simply a binary indication of truth. In the above sentence, it would thus indicate: it is true in the situation on the RHS of the expression that procaspase is recruited and activated.

But we carry a great deal more information than that in the < function. It is a function that is applied to the front parts of the infon on evaluation. There, it does two things, in this order:

First, it colors the meaning of the infon, based on the situation on the left of the turnstile. An example from natural language will help. Suppose we had the two expressions:

< The baby cried >
< The mommy picked it up >

These infons have a different meaning depending on whether the parenting situation is one of comforting or abusing a child.

< The baby cried > so < The mommy picked it up >
< The baby cried > because < The mommy picked it up >

In our example domain, an action infon < procaspase is recruited and activated > may have quite a different ‘meaning,’ and therefore different potential consequences for its host, if the governing situation is one of health, stress or pharmaceutical inducement. All models of fact or event are best valued with consideration to their context. When that context is a system that has coherent system-level behavior, what is represented at the molecular layer can significantly change its interpretation.

The first operation denoted by the <, therefore, is to operate on the ontological dependencies of the (front part of the) infon to modify them to be correct in the context. The second operation of the < function captures the accreted connectives from the previous infons.

This differs from traditional logical notation in one important respect. In the traditional notation, the facts and connectives are separate, thus:

< John is a man > AND < All men are liars >

In conventional logic, these two statements are interchangeable in terms of position; swapping their positions does not change the deduction that ‘John is a man, and therefore a liar.’ The property that allows this interchangeability is commutativity. This means that it doesn’t matter to the truth of a fact — and hence its influence over the deduction — which fact comes first. However, in our system, we allow non-commutative logics because we model processes where:

- What happens before has an effect on what happens after. Intuitively this makes sense because we model processes and it is clear that where things are in the expression is a matter of what brought them to where they are.
- What happens next can change the interpretation or affect of what was stated before. An example in natural language is easy: if late in a detective story you discover the identity of the murderer, it forces you to re-examine what you thought you knew and reinterpret the story so it makes sense. This is the same as saying that each state of a RHS is its own situation in time. Adding another fact (at the end of the expression) changes that situation to a new situated state so that each fact
may be reinterpreted. The importance of this progressive dynamism to interpretation has been examined by Cardier in relation to story structure (Cardier, 2012).

3.4. Infon interpretations are influenced by the LHS

In this section, we introduce the connections between situation equations and their ontological references. One important feature is that these situated considerations can modify their reference ontologies. There are three ways in which this can occur, as indicated by a subscript on <; every instance of < has three components that simultaneously resolve three different types of situatedness, which inform every infon. These are designated: <1, <2 and <3, and capture different influences:

- <1 indicates a direct influence from the situation on the LHS.
- <2 indicates the influence of the infons that came before.
- <3 indicates a retroactive re-interpretation based on the information that came after.

The first of these, <1, is illustrated in Fig. 6a. The diagram depicts the RHS and LHS of our two-sorted, situated expression, with an illustration of a reference ontology imposed above the RHS.

On the RHS of the equation there is just one infon (for simple illustration). This infon informs us that Mary is dreaming (or dreamed or will dream) about a dinner. The LHS is the situation of our speculations about this. (Perhaps Mary told us that every night she dreams about a dinner with her lover.)

The RHS infon is connected to defining ontological terms in the 'tree' above, shown as lines among small circles and squares. Nearly every knowledge modeling system works this way (Sowa, 2006), with a basic ontology and connections that are made in our mind between the tokens we are presented with (in the infon) and the way we connect the dots. What makes these ontologies computable is that the ontological graph is a well behaved mathematical object.

All of these ontological elements pre-exist as bits of what we know about the world in total. In Fig. 6a and b, some nodes are shaded. Shading indicates that the concept is linked into the graph at that moment when we encounter the fact ‘Mary is dreaming about dinner’. The token ‘dinner’ connects directly to our corresponding understanding of what that word stands for, and then spreads out across qualifying concepts.

In our approach, these terms connect as conventional ontologies do, providing interpretive structure for the infon on the RHS. Fig. 6b depicts an ontological graph.

At this point, the example infon is unsituated. We don’t know Mary and we have heard nothing about her romantic adventures, so we cannot assume much about the dinner either. We may tentatively connect some concepts as in the figure: a meal is nourishing and makes us feel good.

We have a local colloquialism that a ‘dog’s dinner’ can indicate a bad situation, but there was nothing in the infon that made us connect to that association. For now, it is a possible but not connected ontological node.

Because the event was notable enough to mention, we suspect that it may be in a restaurant, probably a nice one, which in our experience are downtown restaurants. So those are tentative connections, shown in the diagram using a dotted line.

Note that ‘meal’ can also mean ‘ground grain’ but this is not a remote option at the moment for a component of what the infon means. It is therefore not connected.

The ontology of the relation in Fig. 6a is depicted differently from ontologies of the parameters. This is because the situational information on the RHS modifies the ontological associations on the RHS. For example, knowing that Mary is dreaming about a dinner influences how we connect these elements, because there is some situated information simply in the fact that we are talking about a dream. Elements within this relation are similarly built as a graph, but ‘surround,’ constrain and provide additional context to the parameters already chosen on the LHS.

In effect, the relation does situate the interpretation of the infon’s parameters. But the way it does can be absolutely understood on the RHS, so this one situated influence is not controlled by our < function. (Knowing from the relation that Mary is dreaming about a dinner influences how we connect these elements, because there is some situated information in the fact that we are talking about a dream.)

3.5. How situations bear on infons and inferences

In standard concept modeling, you as the interpreter would make the interpretation of ‘dinner’ once, connecting up the ontology, and that would be that. Current practice acknowledges the reality that you (as the interpreter) may need to revise your interpretation at some point, so complex logical machinery has been proposed. So far, these approaches have been cumbersome, computationally expensive and don’t work all that well, because the logical overhead gets too involved.14

In our approach, there are three ways to modify an initial interpretive reference. We keep the connections temporary and live

---

14 Quite apart from interpretations by humans about motivation, there are many situations at the molecular layer where this non-monotonic situation occurs, see (Kaplan et al., 2008) for a good, very challenging example.
at all times, believing that each new piece of information may shift our interpretation. The role of our $<_{\text{function}}$ is to manage this shifting.

Refer back to Fig. 6a. Let's add more information to say that our LHS denotes a situation where we do personally know Mary, we do know she is in love and that the dinner in question is a special one she had with her lover. We infer, but do not know from Mary, that the dinner led to their first physical intimacies.

Placing the RHS infon in this situation changes our ontological associations in Fig. 6b. The dotted line that connects to 'restaurant' will now be solid because we have prior knowledge that the dinner was in a specific downtown restaurant.

However, a different dynamic is responsible for changes to another part of the ontology connected with the term dinner. On the LHS, there are several non-explicit inferences about this dinner — that Mary talked about it in an excited manner, that she lingered on the sensual details of the dessert. Due to the combined implications of the non-explicit inferences that can be drawn from Mary's demeanor, new information is added to the infon regarding dinner with Tom. In this case, the dotted line between the companionship of a meal together and sex also becomes solid. The LHS operations that account for this adjustment will be explained in a moment.

Our $<_{\text{function}}$ handles this type of realignment of the ontological graph from the LHS. The ontological graph that gave the original interpretation was a mathematical object. The state of our mind denoted by the situation on the left is also a mathematical object (the structure of which we will introduce soon). The $<_{\text{function}}$ takes the original structure of the ontological associations, and applies the structure of the LHS situation to transform the structure of the ontology to give our situated interpretation.¹⁵

This is schematically shown in Fig. 6a by a dotted line of influence that goes from the LHS, through the $<_{\text{function}}$ (which for the time being is by itself) to change the ontology graph. The example is chosen to illustrate $<_{\text{function}}$ because it involves a number of soft objects. This is significant in two respects:

- when the object is soft, it tends to be more vulnerable to changeable interpretation, and
- there is no place to represent soft objects in conventional models of logical reasoning (except for those also accommodated by situation theory).

In this example, our notion of Mary's situation is soft; even our conscious awareness of what we know is soft. Mary's dream is soft to us, and probably even to her. The whole dynamic of falling in love is soft and the concepts Mary may be recalling from her night of intimacy are also soft.

As it happens, humans reason about these things easily. One-sorted automated reasoning systems break when encountering such an avalanche of indefinables. And we haven't even entered the realm of metaphor, romantic fantasy stories and the lack of physical constraints on dreams yet.¹⁶

3.6. Two Other $<_{\text{functions}}$ regarding connectives

Our $<_{\text{function}}$ is not the only situated dynamic at work. It is distinguished from the other operators ($<_{2}$ and $<_{3}$) because its effect comes purely from the LHS. The other two new operators serve as connectives because they use structure collected from the RHS (in the form of other infons) to modify the ontology of a given infon. In the case of $<_{2}$, the infons that modify appear before; in the case of $<_{3}$, they are added after.

Each infon affects every other infon, which is why, in the case that there is more than one of them, we need to apply additional interpretive filters. The extra $<_{\text{operators}}$ come from the fact that we fold our connectives that usually exist between infons, into the infon proper. This differs from the usual notation in which you have facts and logical connectives between them, like $<_{\text{John is a man}}$ AND $<_{\text{all men are liars}}$ THEREFORE $<_{\text{John is a liar}}$. In this instance, AND and THEREFORE are connectives.

The next example features three infons on the RHS in order to show this behavior. These are shown in Fig. 7a — note that this diagram depicts the RHS expression alone (without a LHS). The original infon (about the dream) is the same as the previous example, but now it has two additional, prior influences on its interpretive ontology.

¹⁵ This is similar to the operation suggested in the paper by Hoffman in this issue.

¹⁶ We have an ongoing project to study and formally characterize LHS patterns that appear in these sorts of human interpretations in film (Goranson, 2012a, 2012d).
This RHS expression says: Mary had a meal with Tom, Mary had sex with someone (who could be Tom) and that Mary is dreaming about a dinner (which could be that original meal). (We have implied a ≤₁-informed setting of tense and sequence here.)

In order to interpret this string of infons, the ontology will donate information about dinners, Mary and dreams. This information will situate the hard facts that are known and expressed on the RHS. When we interpret the last infon, we use both together, the facts and the general, situated knowledge. The order in which the infons come to us is also significant to this interpretation. (The order may be the order of discovery rather than the order of occurrence, as in this example.)

In interpreting this string of infons, the <₂ component of the transforming function < takes account of infons that are previous to our original infon, regarding dinner, being one of the two components that substitute for the connective. Suppose the LHS contributes some situational information that enables the <₂ components in the first two infons to carry the ontological equivalent of the following connectives:

< Mary and Tom ate together >
and then
< Mary had sex with a lover >
so
< Mary is dreaming about dinner >

Now, the reinterpretive information carried through <₂ has a great deal of influence over our understanding of the last infon. We have a good idea about what dinner Mary is dreaming about and why. We also have the inference that Tom is her lover and she is dreaming about him, because the dream about dinner carries the notion that the dinner was in some way significant to the relations afterward.

In this case, <₂ adjusts our interpretation of that last infon, performing the same mathematical function we described for <₁. The aggregated collection of the prior infons (with all of its associated ontological graphs with live linkage) is a mathematical object of the same general type (in this context) as our LHS. <₂ therefore works the same way as <₁. It takes the structure of the mathematical object that represents the prior infons and morphs it into the ontology graph, adjusting the interpretation. These are all tentative, persistent mathematical structures that change dynamically based on new information appearing on both the RHS and LHS.¹⁷

The final component, <₃ works the other way. We have mentioned this before, using the latter part of a detective story where a reader reinterprets existing facts after a surprising revelation. Handling of retroactive interpretation is a distinctive feature of our system. Fig. 7b is an illustration of the way the <₃ bears on this activity.

Fig. 7b shifts the focus from the interpretation of the last infon to that of the first. Due to the re-interpretive nature of the <₃, it assumes that we already have a working interpretation of that last infon. Just as existing information can modify a new infon, a similar mechanism allows information to modify old infons.

The example here is trivial: the additional information provided in the second and third infon allows us to refine our notion of the nature of the meal Tom and Mary shared, which pushes the selection of the ontological terms romantic dinner over other possible types of meals. This becomes our new tentative interpretation of that first infon.

There are many cases — both in our natural language and biomedical domains — where events in the present seem to have spooky effects in changing the past. The connective <₃ is necessary in order to model these effects.

The three functions would usually operate simultaneously, where adjustment in the interpretations of what was known before is changing what is known now and vice versa. It is also the case that tentative interpretations on the RHS will adjust situated insight on the LHS and vice versa.

Each of these three functions within the < operator are situated translations. We combine them notationally because we can, because they are generally not orthogonal and because carrying three discrete tokens adds no value to the notation.

These operators are not domain specific and indeed appear to be portable across domains, so the same sorts of morphisms that < would apply to infons about dreams and emotions, would also apply to infons about protein shears.

As an implementation matter, we decompose some internals of < when they are expressed in mathematical form. These decompositions work behind the scenes on the stored tokens in the modeling system. We work at the semantic level (the ontological layer emphasized here), but also at the grammatical layer. All the components of the entire system can be implemented as agents and it is handy to be able to use grammatical roles (where we can) in agent construction. For example, we have already indicated that we leverage the transformative nature of the grammatical object: verb as a transformative function.

Some interpretive colorings deal with tense (a complex matter revisited below) and additionally a concept related to the general stickiness of the tentative interpretive structure, that we informally call trustworthiness. We don’t discuss this latter quality in this paper.

Now we shift to thinking about the LHS.

3.7. Left hand side type systems

The LHS models contexts and the relationship between them. It is supported by a semantic ‘ontology,’ just as the RHS is. Unlike the RHS, however, it is ruled by principles of causal narrative structure, and the way it can attribute agency, rather than Aristotelian logic.¹⁸

The manner in which we identify causal agents is informed by David Herman’s dimensional understanding of foregrounded story figures (Herman, 2006), Einhorn and Hogarth’s theory of causal fields (Einhorn and Hogarth, 1983), and Paul Thagard’s notion of conceptual change (Thagard, 1992). The semantic ontology on the LHS is therefore not governed directly by logic, but by principles designed to manage the interaction and transformation of multiple ontologies: their interrelationships, and the agencies that emerge from them, including projections regarding possible future states. These foundational story dynamics have been described by Cardier (2012).

A core feature of the LHS is that it draws on generically known or encoded structures in order to construct ‘interpretations’ of a specific instance of a phenomenon. In this way, we target the nuances and variations that can appear at a detailed level, and the way these can inform changed outcomes at a higher level. The emphasis on local specificity comes from our analysis of story structure, and the way different renderings of the same plot, characters and events can produce very different interpretations (Cardier and

¹⁷ Internally, what the system does is create a series of state situations for each new infon in a sequence. So we would have a state situation with the first infon, one for the first two and so on. Using this frame of reference, the morphing effect of <₂ is precisely that of applying <₁ from the immediately prior state situation.

¹⁸ For the purposes of this paper, we conflate First Order Logic, Aristotelian Logic, Common Logic and any of their modal variations.
Goranson, 2009). The importance of such effects in textual information has been noted by linguists (Sturgess, 1992; Toolan, 2007). Whenever you have a reasoning system, as we build on the LHS, you need a type system.\textsuperscript{20} For the purposes of this example explanation, it will suffice to describe the three main types of situations within the LHS framework.

Referencing a story interpretation framework\textsuperscript{20}, these three types\textsuperscript{21} represent\textsuperscript{21}:

- \textbf{Standard knowledge and memory}, sometimes known as ‘world knowledge structures’ (Clark, 1996) or ‘common ground’ (Graesser and Keuz, 1993). These structures serve as a general reference for specific instances of the phenomenon (which will be explained in a moment). In molecular terms, this would be the vocabulary of existing models of known behavior in many different ontological domains, including as chemistry and biology.

- \textbf{A real sample}, which is a model of the situation in which a particular biological activity unfolds. The critical point of this situation is that it is not a generic case, it is the raw data related to an actual instance of the phenomenon of interest.

- \textbf{The Interpretation}, which is the situation in which generic, conventional knowledge (such as that drawn from ‘standard knowledge and memory’) are applied to the unique permutations of an actual cell. Matches and discrepancies between the actual and the generic instance are identified here. Possible reasons for the deviations are also recorded here. In this sense, this situation records a new ‘narrative’ regarding the real sample under consideration.

These three situations work together to produce a specific description of real samples of biological activity, informed by tested, standard models. While it is expected that these instances would usually adhere to their expected behaviors, we believe it is likely new permutations in their ‘narratives’ will also arise, as a result of the multiple, overlapping models bearing on them. Our ability to construct new ontological structures, would sometimes produce fragments of novel ‘narrative’ regarding their activity.

In terms of our specific example of olfactory processing, these three types would manifest as:

- A \textbf{Standard knowledge and memory}: An example of an expressible \(\phi\) is a statement about the structural kinematics of protein folding. Collectively, we will call the set of \(\phi\) our LHS ‘ontology’ which populates our new science base.

- \textbf{A real sample}: is the situation of a particular olfactory system with certain described and observable behavior, for instance as we have described here.

- \textbf{The Interpretation}: is our description of the causal laws that apply.

This third type of situation comes into play when we reason over LHS objects. This is described later and for now can be considered the equivalent of \(\phi\) but for the LHS. (Where \(\phi\) situations provide the references (of what is known) for the RHS of \(\phi\) expressions, \(\phi\) expressions perform that task for the LHS.)

Situation instances are designated with as many superscripts and subscripts as are required.

4. Modeling the example

4.1. The question

Our example question is: what is the relationship between the tuning of scent profiles, the apoptotic replacement of neurons and fundamental urges like those associated with romance?

In particular, suppose we know that Mary is deeply in love. She has had a central experience with her lover that was accompanied by the scent of roses. She correlates the two in a clear way: she dreams of her lover and smells roses, and when awake, if she smells roses, she consciously recalls her lover.

Is it possible that Mary’s emotion-driven memory enables a shift to a greater physiological sensitivity to the scent of roses?

Current research suggests that higher brain function correlates with increased acuity of target scents via apoptosis, but no causal theory is within reach. Relating this cycle of emotions and apoptotic refresh could allow for the study of conscious cognition and molecular dynamics in a coherent framework. See for example (Schredl et al., 2009; Liapi et al., 2012; Matsunaga et al., 2011) for representative experiments on sense and emotions.

We also know that every month every sensor neuron is replaced and that there is dynamic reconfiguration of scent profiles based on as yet poorly understood criteria.

We will consider how such a question can be modeled using a two-sorted logic.

4.2. Neural regeneration

The example concerns how olfactory neurons are replaced.

The brain has a central structure known as the subventricular zone, rich with blood and neuronal stem cells which initiate the formation of new neurons, in the form of ‘granule cells.’ These granules move a significant distance through a pathway called the rostral migratory stream, destined for the end of the line as sensors. They move though the olfactory bulb, through the cribriform bone and then take their place, growing tufts to connect and integrate with its neighbors, replacing apoptotic (dying) receptor cells that are being absorbed.

We know that as these new receptor cells take their place, the ability of the sense can adapt or sharpen in certain dimensions. We suspect that they arrive near their final location with information already embedded that helps with this adaptation. In effect, there is one pathway from the area of the receptor neurons which carries information about smells-of-the-moment to the inner brain, being enhanced along the way. There is a complementary pathway from the inner brain where replacement receptor neurons flow back, carrying information to modify the sensor assembly.
We cannot yet say that the granules gather information on the way down, but they surely are given some new situated information at birth when genetic switches are initially set. They may also gather new situated information when they reach their final locale when other genetic switches are set and details of the sensor ligand are determined.23

Some final decisions of what the specific sense profile is to be, seem to be determined at the end stages where the maturing neuron communicates with established ones in an apparent conversation about what is needed.

In fact, some of the maturing neurons have as their sole purpose just this conversation; they interact with their environment to change it, and then immediately die without becoming receptor neurons. They are iteratively creating emerged profiles for other neuron granules that do mature into receptors. As many as half of the new neurons sacrifice themselves this way; we are not absolutely sure of how many and to what extent these shift the sense profile.

And this is not the end. Of those that become mature sensor neurons, about half again die quickly after adjusting their surroundings!

Fig. 8 shows this flow, which is remarkably similar to the flow of sense information, only reversed.

A speculation is that the flow of neuron granules carries information from the higher brain and that complex interactions with the sensor fabric is how that fabric is adjusted to better serve the higher brain functions (Lledo et al., 2006). We do know that there is a clear connection between the appearance of granular cells and the quality and profile of scent perception.

This natural neurogenetic integration process is important. It is studied because it could indicate therapies for brain and nerve diseases: Parkinson’s, Alzheimer’s, Lewy Body Disease, ALS, MS, CF and so on.

We consider this an apt example, because without recourse to reasoning about multiple emergent systems, there is no way to comprehend the complex combination of molecular processes that must be coordinated.

4.3. An outline of the approach

We start by building a vocabulary of LHS dynamics, building from what we can extract from known RHS behaviors. In this example, those RHS behaviors will be represented by three types of RHS expressions.24

Two of these RHS expressions are from known molecular dynamics, modeled using infons. These two dynamics are: an expression that describes the behavior of molecules when one of the components of roses are sensed; and, an expression that describes genetic switches set during apoptosis that modify a neural granule, so that it can be targeted for that scent. The third expression is of our subject’s emotional profile.

These three contexts have incompatible ontologies in that the terms of one do not translate into meaningfully into another (molecular scent detection, molecular cell death, emotional psychology). Our approach allows them to maintain their separate local vocabularies, relating them back to a common situation on the LHS.

Fig. 9a shows this schematically: the two molecular expressions next to each other, with the emotional expression placed above. Each will be expressed in different terms, using different ontologies.

---

23 The ligand is the business end of the process. It fits on the surface of the cilia of the receptor neurons and is the molecule that actually senses the airborne molecule based on relevant geometries.

24 In practice, this would be three groups of RHS expressions with orders of magnitude more information and detail. We simplify for clarity.
Fig. 9b illustrates the extraction of causal connections in three distinct situations (the triangle) which are then related by some global causal dynamics (the center of the triangle).

Fig. 9c shows this common system dynamics transposed back to RHS expressions, describing the influence (if any) of the emotional profile on the scent detection profile, as determined by apoptotic regeneration.

Mapping back to the RHS produces a set of expressions that provides new information about the overlap on causal dynamics, including specifications that can be tested by experiment when expressed at the molecular structure layer.

This is the example we will step through using formal mechanisms. We have a pair of tantalizing genetic processes, each with some important unknown factors. In the process of sensing a molecule, some signals are sent that we know control genetic switches, but we do not know their scope or purpose. As the olfactory system regenerates, we know certain genetic switches are flipped but we do not yet know how. Possibly, these are related. When we form our infon expressions for the sensing and replacement processes, there will be a placeholder in each for these unknown genetic mechanisms, presuming that at the end of the example they will be ‘filled out.’

4.4. The example: methodology

Stated succinctly, the aim is to use both sorts (LHS and RHS) to help us design experiments in order to identify the mechanism, should one exist, whereby emotional state changes olfactory sensitivity via apoptosis by traceable cause.

Our strategy is to:

1. Capture known, relevant dynamics in situations at the emotional and molecular layers. Large numbers of relatively simple RHS expressions are preferred.25
2. Build some target metaphors at the information flow layer for a workable RHS theory of how concepts affect the neural fabric. (In the next subsection we describe the methods for building these different RHS expressions.)
3. Concentrating on the LHS dynamics, we build (the equivalent of) a LHS ontology, using the large collection of iterative morphisms from observed behavior.26
4. Express on the RHS — as a type system — some laws as they are discovered from that LHS ‘ontology’ in situations that reveal those dynamics (in logical statements).
5. Perform morphisms to map those dynamics into the newly designed type system for our information flow layer. We would now have a working model of emergent phenomenon, based on the current science. (This is the first INBIOSA goal, as noted below.)
6. Test other targeted morphisms in situations that describe similar behaviors in the molecular layer, in order to create speculative RHS causal flows. These speculative situations will be the basis for experiments that, when performed, provide new tentative facts that can be tested. (This supports the second stated INBIOSA goal.) Registering these facts into the knowledge from the first step modifies everything in the system, because all morphisms are persistently dynamic.
7. Iterate, growing a workable theory of information flows that results in semantically describable emergent systems, which are informed by and describe living systems, as well as their perceptions of the worlds that contain them.
8. Apply this new theory in therapeutic domains, perhaps for neural regenerative responses to serious disease.

The example spans several levels of emergence. We will now represent some of the details that characterize each layer, before ‘combining’ them in our two-sorted logic.

4.5. Layer 1: molecular biology

We model three layers, which can be said to exhibit emergent behavior when one is compared to another. The two molecular expressions occupy one layer, and the emotional response occupies a second ‘higher’ layer (in the sense that it concerns higher brain function). Later, a third tier, expressing information flow, will be placed between them.

The first expression concerns molecular scent detection. The below example shows the structure of empirical potential energy function (Steinbach, 2010) within and among molecules. These functions — when seen at this layer — drive all known biomedical processes. They are based on the interactions among atoms and simple parts of molecules: bonds, angles, improper dihedrals, torsions, electrostatics and van der Waals forces.

This diagram shows the relationship between naive symbolic chemical expression (seen at the top of the figure) and the model in our notation (position at the bottom of the figure). The relation in the infon is designated p, and the two elements are indicated by a.

25 The reason for this preference for many simple expressions is that experience shows that complex RHS expressions do not scale well. In fact, this is the reason for the second sort in the first place. Throwing as much of the scalability problem into LHS morphisms is conceptually and computationally cleaner. The reason for not creating expressions with mixed RHS infons, using different ontologies, is that they cannot employ our second and third component of < (where surrounding infons affect the interpretation of every infon) without implied virtual intermediate situations.
26 The most significant novelty of the approach is the concept that these laws are built by observing and characterizing morphisms which capture ‘narrative causal agency and impetus.’ See (Cardier, 2012).
In representing this form of the molecule, we have shifted contexts, from that of molecular potential energy, to that of higher level structure. This figure shows that the parameters of the relation — just as with the potential energy function — have ontological types that are fundamentally geometric. The infon that represents it captures how the structure of a caspase is functionally characterized, structuring dynamics, constraints. We chose these two because they are without controversy, can just as well with common entropy and energy constraints here as well, (Nawroth et al., 2007).

The third type is foundational to the information flow dynamics, expressing some of the LHS dynamics. Because the LHS dynamics are system-independent, this information flow type is as well.

Relevant characteristics of this type were mentioned earlier: contextual conflict, integration and generation, and the identification and support of causality and projection. The type system of the structural and emotional layer allows us to move from RHS to LHS. The type system of the information flow layer allows us to move from the LHS to the RHS. We revisit the information flow layer later.

The three infon types (for this information flow layer) are illustrated below. We show them first in their informal form, then in the structured infon:

\[
\langle \text{A receptor neuron is excited by acetone} \rangle
\]

\[
\langle \text{Ccpp: \text{Dmax}, \text{theocone;}} \rangle
\]

\[
\langle \text{A mitochondrial apoptotic pathway signal is sensed} \rangle
\]

\[
\langle \text{Ccpp: \text{Dmax}, \text{theocone;}} \rangle
\]

\[
\langle \text{A spatio-temporal sense pattern is sent from the olfactory bulb} \rangle
\]

\[
\langle \text{Cneuron: \text{Portbulb, Bacetone;}} \rangle
\]

\[
\langle \text{A pleasant memory of the scent of a rose is stored} \rangle
\]

\[
\langle \text{Cpaltm: \text{Pramyg, \text{thosm;}}} \rangle
\]

(The mnemonics for the components within infons thus far introduced are:

\[p = \text{potential energy function}; \ a = \text{atomic unit};\]

\[m = \text{(molecular) morphing function}; \ s = \text{structure};\]

\[c = \text{(information) channel function};\]

\[p = \text{pathway or position}; \ e = \text{signal type}\]

The four statements above are:

- As an aggregate of molecular dynamics (agg), an olfactory receptor neuron (m) has become excited (x) in mode a (a) (pulsed mode) by interaction with acetone molecules (in the nasal cavity). Later, this can be used as a situation: 'in the situation where so and so,' or zoomed/explored into the series of structural mechanics that it represents.
- As an aggregate of molecular dynamics (agg), BCL-2 regulator proteins are carrying a signal to trigger cell death. Because it is an aggregate it can also be situated or exploded.
- A neuron serves as pathway for a signal from the olfactory bulb conveying the information that acetone has been sensed.
- A memory pattern is currently active in the right hemisphere of the amygdala, such pattern associated with rose memories.

Our selection of these two types of structural functions is not prescriptive. A practitioner could parse the structure in many number of ways consistent with infon constraints. We chose these two because they are without controversy, can completely characterize structural dynamics, fit well with common entropy and energy-based computational ontologies and tools and revert to intuitive UI conventions.

A practitioner could include purely chemical signals in this layer, but that decision introduces additional ontological features that are duplicated at the structural layer. All of this is a balancing act between keeping the two-sorted system clean and simple and maintaining an intuitive mapping between current representations and infon expressions.
factoring these ordinary behaviors this way provides some
notable benefits even before we apply the second sort.

Assuming that the type system and connectives are well or-
dered, with these two layers, we have a functional model that can
capture the dynamics that practitioners use. So an expression of the type:

$$\phi_{\text{process}} = \frac{(\text{LHS process})}{\text{RHS process}}$$

$$\text{RHS process} = \frac{(\text{motions}, \text{emotions})}{\text{motions}, \text{emotions}}$$

$$\frac{\text{process}}{\text{RHS}}$$

can be used to capture any sort of currently simulated process. The expression would be read as “the situation of the described process
is partially described by the following RHS, consisting of a sequence
of type: $\text{process}$.” Or simply that any process can be described by a mix of energy potentials, structural interactions and signals.

This would also include the following law:

$$\frac{\text{zoom}}{\text{motions}}$$

$$\frac{\text{motions, emotions}}{\text{motions, emotions}}$$

$$\frac{\text{process}}{\text{RHS}}$$

Which would be read as “as a law of the system ($\phi$), the following at least is true: an $m$ infon can contain as an element a
statement consisting of $p$ infons, and also a $c$ infon can contain as an
element a statement composed of $m$ infons.” Or in other words, a
model consisting of information flows (or signals) can be zoomed in
to be modeled as molecular structural dynamics which in turn can
be zoomed in to be modeled as energy potentials.

Such LHS situations as functional expressions can be formally
analyzed for such qualities as completeness, correctness, cost of
computation and so on. This is a significant benefit. Traditional
notions of hierarchy and emergence are completely subsumed.

4.7. Layer 3: emotional/conceptual model

So far, we have described the ability to model situations concerned
with structural dynamics and energy potentials, and also situations described by several types of information flow in
systems.

Here we introduce an additional layer, one of concepts, stories
and emotions. The structures that underpin this framework directly
evolved from the mathematics of situation theory, which has been
extended to include dynamics common to narrative cognition. (The
importance of situation theory to our work is discussed below, in
the section on influences). The type system in this case is rather
large and well developed; it is based on natural language, which is
our universal paradigm for expressing systems of concepts.

You have already seen some concept infons.

Below is an example expression:

$$\phi_{\text{observation}} = \frac{\text{Mary slept}}{\text{she dreamed}}$$

$$\frac{\text{the narrative of the dream}}{\text{the narrative was driven by strong}}$$

$$\frac{\text{emotional urges}}{\text{emotional urges}}$$

For the purposes of this example, we focus on the way humans
can have their emotional state changed in response to scents. In
addition, dreams can be affected by scents in such a way that the
effect presents as an influence on emotions, which in turn affects
the dream’s narrative.

We know that humans — indeed all mammals — change the
tuning of their scent perception at some level based on what
matters to them. The smell of a lover or a child comes to be
regarded as comforting, as does the smell of food cooked in
nurturing environments.

The physical tuning of scent, however, requires apoptosis, and
involves the generation of neural granules from stem cells, in parts
of the brain associated with emotions and narrative. In this way,
apoptosis could participate in ‘olfactory tuning.’

We do not know whether or how emotion affects the actual
receptor neurons. In this example, Mary’s olfactory system may
adapt to be more sensitive to scents associated with desired
memories, based on signals influenced by these memories. In order
to model this effect, we need to be able to combine information
from all three contexts, including her memories and emotions.

Even without introducing the second sort, our systematic
approach would allow formally-based reasoning over these three
contexts, each with a quite different set of ontological assumptions:

- the molecular thermodynamics that have emerged from eons
  of specialized selection (and the associated reasoning about
  that evolutionary process).
- a model of agents and information flow that can serve as a
  surrogate, capturing the emergent behavior within the system,
  and of external forces which created the larger system (by
  evolution).
- a model of emotions and urges that influence cognition and
  human reasoning.

These strings of expressions are inter-related on the LHS. Let us
now turn to the advantages of the second sort, our LHS.

4.8. LHS reasoning

This section describes the formal underpinnings of the
semantic-like ‘ontology’ on the LHS.

Much of the world can be supported by RHS logic; that is what
physics is all about. Adding in the situation theoretic LHS gives the
ability to represent the open set of knowledge about behaviors that
we commonly reason over. The open set implies that there are
behaviors and structures on the LHS that are not expressible on the
RHS.

When such situations appear on the RHS (a so-called ‘soft ob-
ject’), it appears as an aggregate of facts that cannot be fully
expressed or logically explored.

For example, an expression with a \(\phi\) apoptosis situation on the
LHS would be the modeled situation of normal olfactory receptor
neuron apoptosis, while the RHS would be what we know about
how that process unfolds. We know a great deal, so the RHS would
be large. But we don’t know everything; it may turn out that we
miss some key behavior of interest. The LHS situation in this case is
the open set of knowledge about apoptosis (and other things).

Yet we can confidently perform some reasoning about what we
know by placing that situation (\(\phi\) apoptosis) in infons on the RHS.
Intuitively, the symbol is just a reminder that we are dealing with
partial unknowns. Formally, supposing you are analyzing your
reasoning (for instance for meta-studies), it provides essential
bookkeeping for the logical analysis.

But we propose a more fundamental advantage to having a LHS:
the ability to reason differently. Even though it is not the same kind
of reasoning as the logic on the RHS, it is valid nonetheless, and
probably much like how we actually think.

The reasoning on the LHS produces statements about condi-
tional knowledge — conditional because it captures a situation
through a representation of the multiple perspectives that bear on
it, and for a limited duration. The restrictions entailed in this con-
ditional perspective are further limited by the way they are in
transition, and will change their relationships when the next piece of information appears. We refer to these transitions of overlapping, limited inferences as a form of narrative reasoning (Cardier, 2012), and like Herman and Bruner, assert that this mode produces a different yet valid means of understanding from logic (Bruner, 1985; Herman, 2006). Its structures enable us to capture transitions facilitated by causal agents, and produce situations of limited representational scope, which are also able to transform beyond that scope.

To support this, we constrain the RHS to be both linear and intuitionistic.

The RHS is linear in that the position of the facts is significant. It is non-commutative, because the framework for interpretation can change as each new fragment of information emerges. An event that comes before another is thus considered to be a potential cause. If we were working with a Bayesian-structured RHS, the connectives would be probabilities (‘this x has a y probability of being in the exclusive set of causes’) that are dynamically adjusted. We can subsume the Bayesian connectives with a more semantically formal notion.

This linear quality allows us to construct causal lattices of the infons, and by extension, all their explosions to primitives, all their infon elements and all the ontological roots each has. A representative of such a lattice is on the right hand of Fig. 10. You would read this starting from the bottom and temporally moving to the top. Nodes are infons and lines are $\prec$-mediated connectives.

Our RHS is intuitionistic as well. This means the semantic interpretation of any infon is subject to change, based on context, as our $\prec$ function is applied. These two qualities allow us to abstract structure from the RHS to any number of categorical spaces in the LHS.

Abramsky and Coecke (2008) use a similar approach to physics, using monoidal categories. Other categoric objects are used by others (in physics), using a weaker notion of a LHS than ours. Our goals (in the case of this example) allow our LHS objects to be mathematically simpler than those of Abramsky. Fig. 10 shows the half-dual of the causal lattice. For RHS/LHS consistency, in the figure it is on the left (in red).29

A convenient way to think about this RHS structure is to think of the RHS as describing causal relationships in logical (read: Newtonian-physics-like) terms. Each link in the derived lattice is a (potentially) causal link. Taking the half-dual essentially turns each of these causal links into an element in a contextual structure.

Together, the LHS objects capture the structure of causality, without any of the semantics of the original elements.

Such LHS objects collectively comprise a universe of causal agent structure. Because they are scrubbed of the RHS semantics, applying set-theoretic logic is moot. Instead, we take advantage of the fact that these objects are categories and that we can have a formal vocabulary of operations among them.30

Mapping from the RHS to the LHS is a category theoretic morphism. Comparing any two LHS objects is also a morphism. So for example, we can have a situation of Mary’s emotions, with some RHS descriptions but the situation is presumed to be mostly soft. This is because we know some things about her emotional state, but not all.

We can imbue much of the structure of the emotional ‘story’ of the LHS by comparing it to a great many emotional experiences of Mary’s (and any number of other people). We assume that some sort of categoric ‘laws of represented emotion’ will emerge from this cohort, similar in quality to laws of physics. These will just be expressed as categoric morphisms rather than logical statements.

Because it is indirectly modeled, the concept of ‘emotion’ is somewhat artificial. We only know of emotions by their effects. It is fair to say that in our minds we have an expression with an imputed emotion on the LHS, and some facts associated with that emotion on the RHS.

\[
\phi_{\text{happy}} = \langle \text{feel good} \rangle \quad \text{and} \quad \langle \text{optimistic outlook} \rangle \quad \text{and} \\
\langle \text{pleasure chemicals measure high} \rangle \quad \text{and} \\
\langle \text{smiling is frequent} \rangle
\]

Emotions are comparable to fields in physics, both being a concept of theoretical necessity but not direct observability. Like emotions, we know fields exist, but only by observing effects that can (it seems) be explained by their existence. This adheres to our perceptive stance of the LHS. We list the known details that can be observed, on the RHS. On the LHS, was find structurally analogical matches for those combinations of elements. The common elements of structure between these situations is expressed as category theoretic morphisms.

LHS category space has dynamics. For instance, we know there to be a collection of relationships among different emotions. Though some logical things can be said of them and their relationships, such an understanding of emotions escapes ordinary logic. We can, however observe many emotionally-driven narratives as RHS side statements; we will use this in the example.

4.9. Known RHS dynamics

Our system depends on the use of existing ontologies to generate sample-specific narratives regarding cell behavior to build beginning LHS dynamics. This example therefore requires a corpus of existing ontologies that would contribute to this structure-building endeavor.

There are three tasks associated with the establishment of this repository:

1) Collect knowledge: facts, correlations and causes.

---

29 Our general method is highly categorical. The examples here reflect the belief that the $\phi$ categories can be simple objects. Our RHS lattice is a skeletal category; since a goal is to host computationally efficient and complete applications, this is ideal.

30 Categories are objects that capture structure. Operations between categories are transformations of those structures and (in our case) are called morphisms. A great many types of morphisms exist. (Strictly speaking, relations within a category are morphisms and relations between categories are functors. But our categories themselves exist as elements of categories so for convenience we use the ‘morphism’ for all operations, and compose them together.)
Very little factoring is required for this step. It is not essential that the variables be independent, the facts orthogonal or ontologies of different layers thoroughly harmonized. Because we accommodate existing methods, and because approaches to first-order ontologies in the biomedical community are relatively standard, this is a straightforward effort.\footnote{Any well-formed ontological basis can be used. This example relies on the frameworks exemplified by the Gene Ontology Consortium (Ashburner et al., 2000). The more common of these frameworks are process-linked rather than property-linked, so the ontology cannot be directly leveraged for zooming. For example, the structural folding of a protein is not ontologically defined in these frameworks as an assembly of empirical potential energy functions, as we specify above. Such ontologically based zooming would have to be synthesized from additional ontological reference, normalized to binary relations. These will probably appear in the biomedical community in the longer term.}

Fig. 11 shows two example ontology trees that are relevant at the molecular layer, one for caspase structure and the other much larger below for one of the relevant genetic structures (AATF).

2) Factor the known information into our binary relation based infons.

Given well-formed ontologies, an automated tool can aid in this. For well-practiced domains, this can happen behind the scenes, allowing the practitioner to interact with more familiar syntax. As it happens, we assume that the example ontologies are encoded using OWL, the semantic web ontology. OWL implies that each ontological relationship can be (and often is) expressed in the Resource Description Framework which maps directly to our binary infons.

3) Catalog the connectives (to be subsumed in \(<_2\)).

This last operation is also straightforward. To remind, \(<_2\) is the transformative function that acts like a traditional connective in linear logic. It is therefore a presumed causal connective, which we can simplify here as ‘and-then’ (Lehmann, 2008).

This ‘and-then’ connective is what is implied in normal process models where one step at least partially ‘causes’ a following step to occur, as we sketched in Fig. 3.

The full expressions will all be of a behavioral situation type \((\varphi)\) and have some typical characteristics.

4.10. Extracting infons from the corpus

For the biomolecular layer, structural dynamic infons would dominate, though the modeler could for convenience aggregate up and have signal infons that contain many molecular dynamics, or zoom down to have many component infons that describe details of the energy functions.

An example would be a series of infons that describe the steps involved in the capture of a target scent, as follows...
In our example, we assume that some expected advances have been achieved on the structural type system. But otherwise, most of the usual major problems of scalability and decidability do not apply because of the way we approach the problem.

4.11. Connective reassignment

Having extracted infons to support the RHS, we now need a means of relating them. In order to morph them to our LHS, we collapse all instances of each operator together. All the rs, ps, ms and < functions in each infon are combined as described below.

In the case of the < function, there are also three different modes to consider. These are:

- The <1 function carries only an ‘experimental truth’ value; that is, the infon ‘is a true process (or fact)” in the situation it describes, not modifying the apparent ontological assignments.
- The <2 function simply conveys the ‘and-then’ or ‘while’ connectives. This is intuitively simple, and functions here in a straightforward manner. (The ’while’ connective denotes concurrent processes that are apparently not forward causally connected.) But we should remark that these simple operators indicate a non-commutative, non-associative boolean algebra such as suggested in Baianu et al. (2006).
- The <3 function is null in these kinds of expressions because the expression captures what was observed. We likely will modify what we know about internal machinery later, but we will not modify the fact that at this moment, we have observed so and so.

When the < function is integrated, each of these three instances is applied.

Expressions for molecular biology and emotions are different from each other, however. Below is an example of the structure of an expression of observations at the emotional layer:

$$\Phi_{m} = \{ \ll m : i_{1}, i_{2}, \ldots, < 1, < 2, < 3, \ldots \} $$

The ‘collapsing’ process must be able to brook the differences between this and our infons for molecular dynamics. In order to appreciate the range this entails, consider that in our example, the situation is a specific encounter between Mary and her lover, where the scent of roses was dominant; it is also a situation wherein our person in love subconsciously believed herself to be.

Each of these is amenable to presentation as a linear narrative in natural language. Relations r and parameters i at this layer should have ontological assignments identical to those we would use to reason about and describe the work in first order logic, emotionally and/or clinically based.

Examples of r may code for real events like eating or physical intimacy. They can capture events in the fantasies that are associated with that individual’s notion of love, perhaps taken from a movie genre, which then must also form part of our ontological reference corpus.

In order to collapse these situations together with those from molecular biology, we focusing solely on the similarities in the infons, which are structural: the r, p, m and < function in each infon.

All infon parameters can be zoomed, so that initial statements reveal their underpinning structures. It is useful to think of each unsituated infon in a refracted way:

$$f(m, p, r)\{\{(a_{1}, b_{1}), (a_{2}, b_{2})\} \}$$

f is the relating function from the set, so far, m, p or r (m and p are structural, and r is conceptual). f operates on appropriate pairs from
the set of a, s and i. (a and s are structural, and i is conceptual). The function

\[ f(x) \]

Can be considered a double as well

\[ (f, x) \]

\[ F \text{ is a set of operators } \{f\} \text{ which recursively define the ontology} \]

\[ \text{to a arbitrary depth.} \]

\[ F = \{(fn, x)\} \]

and any parameter is ontologically defined by a subset \( O \) of possible doubles, \( \odot F \), where \( O \) is a directed acyclic graph. Instances of \( O \) for the layers overlap, as they share fundamental notions of entity, identity and sequence as well as higher order concepts like attract. We need not go into more depth on the RHS as this is all from mainstream foundations other than to note that \( O \) constrains the type system of infons. Also, as a practical matter, for highly introspective systems, we allow \( O \) which recursively define the ontology

\[ \text{O is generally noun-oriented. We form our } F \text{ from the verb-oriented subset of (or synthesis from) } O. \]

Thus, we can build a lattice from any RHS expression. These techniques are well known, and sufficiently mainstream to form the formal basis for the long-promised Semantic Web. See (Sowa, 2000, 2011; Wille, 2005).

4.12. Level 2: details of the information flow in

It is now time to elaborate on the composition of the fundamental infon relation in our information flow layer. You will recall that the first type in this layer is simply an aggregation of known physical infons, collapsed for convenience. The second is a model of a physical signal within the neural fabric. There is not much choice about the nature of these.

The third model is wholly synthetic. A goal of our example is to create a model of information flow within overlapping living systems that captures emergent behavior. This is where we determine what we mean by information, flow, emergence and ancillary concepts (including tense and cause).

In later sections, we note some models of information flow developed by others; some are quite complex. For the present example, we use Barwise’ relatively straightforward concept:

- information in a system consists of flows through channels. (Flows and channels are metaphors leveraged for modeling. We model these with the infon \( \ll c, p, e \gg \) as the flow, \( c \) (the relation) is the channel, \( p \) is the pathway and \( e \) the signal.)
- Depending on your perspective, intelligence or information conveyance in a system is a combination of these flows working in concert. (Our categoric structure generally follows that of Barwise in (Barwise and Seligman, 2008).) \(^{32}\)

This step of the methodology, in which we export new dynamics from the LHS, results in three products in relation to this example:

- a general theory of information flow for the combined system of emotions, concepts, neural patterns and molecular dynamics.
- a specific theory of information flow for the system of interest, here our combined emotional-olfactory system. This is presumed to be primarily modeled in terms of concepts and molecular dynamics (as a result of our earlier steps), but informed by the information flow model. This approach is designed to encompass both explanations of known observations and speculations on future observations.
- an experimental plan to test and extend the theory. This could be expressed in emotional terms, but we presume here that the final expression is in sequences at the biomolecular layer that can be tested by standard protocol.

In our example case, our channels (other than the summary and neural channels) are reverse engineered from the notion that a signal needs to make a difference. Because this variety of signal is abstract and not directly measurable, the effect can be abstract also.

For instance, one of our behaviors of interest conveys information about a target scent to a region of the brain where emotional memories are stored. A connected behavior of interest is the way that emotional memory is related to other memories in narrative structures. We would also be interested in the behavior of how these (or related) narratives send information to newly reconstructing olfactory receptor neurons.

Within this kind of infon, and in the graph through the ontology, first order logic applies, the statements are monotonic as usual, but the links of the graph are frangible, so that as context is applied, the meaning is re-adjusted. This is how we shift the essential non-monotonic nature of the system to the second sort where it is trivial.

We follow the same rules for our information flow layer and the infon type \( \ll c, p, e; \gg \). (The c relations are constrained in a common sense way not detailed here, and as described in Barwise and Seligman (2008).)

We can thus rewrite the function (of an unsituated infon at the information flow layer as

\[ f(\{f, m, r, o\})(\{x_1, x_2\}) \]

Which is to say that when we model the olfactory/emotional complex at the information flow layer, the relation is a function over a hidden mix of infons at the other two layers plus their ontological linkage, a huge lattice for the explicit infons and a larger directed graph through the ontologies. For notational economy, we write this as \( F \), thus:

\[ \{F_n; \gg \} \]

That is, a situation is supported by an ordered set of our logical links, modified by our \( \langle \) function.

The lattice is our first class object in situating what we know, so we can write:

\[ \langle \langle 1 \langle 2 \langle 3 (\{F_n\}) \rangle \rangle \rangle \]

... that the real structure of the RHS is a series of lattice-ordered infons that model the emotional/olfactory system in terms of Barwise’ information channels, that they in turn are decomposable into ordered series of statements about observed molecular and emotional behavior... and that so far as situating those infons, you need to first apply the \( \langle 3 \) function which changes the graphs based on the imposition of new information, then \( \langle 2 \) which similarly changes the graphs based on old information, then \( \langle 1 \) which changes the graphs yet again based on contextual constraints passed from the LHS, or more cleanly,
This hides the deeply recursive nature of the object’s definition.

4.13. LHS case discovery

This and the next step of the methodology are linked and can be performed simultaneously. One creates formal expressions from RHS statements, while the next morphs those expressions from the RHS to the LHS. We separate them because they each use different morphisms. In this step, the morph from RHS to LHS is also a move from the logical expression to the category, one each expression.

These expressions work both ways. You can use them as we do here, which is the usual way: to definitionally say something we know about a specific situation. The flow of information in such an expression is from RHS to LHS, with the structure of the LHS extracted from the RHS. Later we shift in the other direction, by creating new LHS objects by LHS operations, and the pulling out to the RHS what we can say in terms of logical, fact-based expressions.

Our mechanism for this right-to-left structural extraction is our familiar \( < \) operator.

The category of \( \emptyset \) is the half-dual of our RHS object, which we write as

\[
p : (\langle \{F_n, \ldots\} \rangle) \leftrightarrow \emptyset
\]

\( P \) is the set of \( p \) morphisms that transforms the structure of our RHS to the structure of the category on the LHS.\(^{33}\)

Now we have our LHS objects. There will be many of these. For example purposes, we have described nine. Three are from the structural layer as recast in the information flow layer, for our example:

- The detection of \( \beta \)-damascenone, a signature component of the smell of roses;
- The morphing of caspase-6 to destroy a soon-to-die receptor neuron; and
- The genesis of a new neural granule from a stem cell.

We have three from the emotional layer:

- A woman in her own narrative of love;
- A specific encounter with her lover that involved the scent of roses; and
- Her notion of who she is in the world.

These six are recast through the information flow metaphors. We have three that are native to that layer:

- The transmission of the scent of roses;
- The recall of that scent; and
- The high level signal from the brain to increase sensitivity to that scent.

These can be factored in implementation code, extracting (in this case) our half-dual. All we are doing here is taking each RHS side expression — which collectively is all we know — and building an instance on the LHS.

The collection of these LHS objects should reveal something about the causal structure of the interleaved systems involved, when they are considered together. In this step we simply generate and recognize all the situations-as-categories within our knowledge.

As a practical matter, RHS expressions should be exhaustively creatable from existing references such as the Gene Ontology or some combination of protein databases that captures generational behavior. And this structural step should also be fully automatable. So all the \( R \) relations extracted from the RHS come ‘for free,’ as part of the existing corpus of information already known about apoptosis.

Also as a practical matter, we keep the LHS cases that originate from the emotional/concept/narrative layer separate from that of the molecular interactions. Structurally at this stage they are identical, but in the next step we enrich by observations that will report and add different dynamics in these layers.

The LHS cases capture the laws of the open set of RHS expressions, including those that are yet unknown.\(^{34}\)

Fig. 12 shows the kinds of objects defined so far, plus the \( R \) morphisms discussed next.

4.14. LHS structural dynamics

The primary value added from the framework is contributed in this step.

The previous step produced a collection of LHS \( \emptyset \) situations, each of which with causal structure that was characterized by a

\(^{33}\) The mnemonic is that \( p \) stands for the ‘provenance’ of the infons, the coloring afforded by properly situating them.

\(^{34}\) A tacit assumption is that there are persistent laws in the system, which is a fair assumption in our example domain. We have considered domains where systems exhibit emergent behavior, while at the same time the laws that govern them are emerging. The effectiveness of cinematic narrative (Goranson, 2012d) is such a domain.
mathematical object. Some of the relationships among these \( \phi \) objects may be state transformations from one state of a system (in a given layer) to another, as a process progresses.

Some of these situations will be related by known correspondence but unknown mechanism, like the relationship between neutered olfactory sensors and psychopathy (Mahmut and Stevenson, 2012). And many others may be related in unknown or even unsuspected ways, like our emotional profile and apoptotic imperatives.

Now we add LHS dynamics based on the same scientific rigor we (with others) use on the RHS, and capture these situation-to-situation relationships as morphisms between (or among) the categories that represent these situations.

This is a fairly simple matter when a chain of events is already explicitly specified on the RHS, for instance those as shown in the apoptosis process depicted in Fig. 2. (In this case, there can be a one to one correspondence between a RHS and-then additive and a LHS sequential morphism. But this generally will not be the case.)

Each of these morphisms is denoted by \( r \) with the set of \( r \) being \( R \).  

A large number of such situation to situation mappings exists. Some are inherited from the process just described as reflections of RHS dynamics of \( \phi \) objects. Most of the others are relationships that bear on the system but which have no current RHS expressions.

Other \( r \) morphisms will be entered by a talented LHS-aware modeler with a familiarity with the \( \phi \) objects using tools such as those described below. Over time, decomposition into components with internal relationships becomes apparent.

Our dynamics for concept storage (in the mind), internal narrative and its presentation in fiction is illustrative. We assert elsewhere (Cardier, 2012; Goranson et al., 2012) that the dynamics of systems that elude ‘logical’ modeling becomes tenable when observed through the lens of LHS dynamics. This follows the observations of Barwise and Devlin (and others as we note below); all we have done is build a formal implementation and (partially) explored some LHS dynamics. (This approach also makes any non-monotonic or non-deterministic behavior on the RHS easy to implement.)

As it happens, these \( R \) dynamics also apply to our cognitive/ emotional layer \( \phi \) situations as well as our \( \phi \) situations at the molecular layer. (To remind,

- **\( \phi \)** situations are the real instances of behavior we are studying.
- **\( \phi \)** situations are (roughly speaking) statements of generally known laws that apply over objects in those situations.
- **\( \phi \)** situations are the expressions we make to describe how those general principles apply to particular real instances. It also includes additional information in regards to the interaction between the whole systems involved, as expressed on the LHS. In this example, \( \phi \) situations over the molecular layer could be the ‘stories’ expressed when we impute emergence, self-organization or the common notions of evolution via selection. The structural biology community often calls these ‘movies.’
- Every RHS has a \( \phi \) via a unique \( p \).
- An explicit \( \phi \) is a sequence of \( r \) between \( \phi \), observed in the domain.
- Every \( \phi \) has a sufficiently complete RHS expression.
- Every \( \phi \) is a category of relevant \( r \) in \( R \).

- **\( R \)** is a category and subset of the category of \( \phi \).
- **\( \phi \)** may be expressible in certain RHS ‘geometric logics’ mentioned below in the note on quantum interaction.

Therefore, this step requires expertise and patience to create a corpus of instances of our foundational dynamics in the LHS. Unlike the previous steps, this cannot be automated. A cookbook on our LHS framework is beyond the scope of this paper, but some general principles are:

- The LHS situates situations. It tracks relationships among multiple systems in a manner similar to the way a RHS ontology depicts relationships among concepts.
- Situations on the LHS are in transition. The terms on which their interpretation is based are changing, so rather than determinations of fact, they exhibit features of agency in relation to change. Cardier argues that these transitions are causal (Cardier, 2012).
- Situations on the LHS utilize their ontological limits. Their purpose is not to establish ‘objective’ facts, because their focus is on relations among multiple modes of expression. The information that emerges is thus a ‘narrative’ concerning the series of causal transitions needed to move from one aspect of a situation to another. The LHS characterizes the nature of that agency, and the way it changes as the process progresses.
- A primary dynamic in relationships among situations is governance, where one situation governs others imposing its associative priorities. Governance is a means by which causal agency is identified and characterized.
- The focus on transitional attributes and governing influence, leads to determinations of causal impetus, so that possible outcomes could also be projected.
- Related dynamics are (apparent) precedence and dominance.
- The \( \phi \) dynamics often retrospectively change the effect of \( r \), producing effects often characterized as ‘quantum’ (or spooky).
- Temporary and tentative situations come and go.\(^{37}\) Their non-explicit presence informs structural ‘choices’ made in order to situate situations on the RHS.
- Ontological assignments on the RHS are relatively fluid.
- RHS ontologies form groups and layers in response to the exercise of \( r \) dynamics.\(^{38}\)

We have designed a number of user interface metaphors and tools to support this process; they are described below.

### 4.15. RHS information flow statements

Until now, we have been working with structure on the RHS as extracted from the RHS. In the previous step, we then enriched it with new RHS structure.

Now we take advantage of that new structure and transfer some of it back to the RHS, where it can be used. This subsection addresses that process.

Fig. 13 shows \( \phi \) categories as small pentagons with \( r \) morphisms between pairs. A collection of \( r \) as \( R \) is a category itself, shown as the large dotted pentagon.

\(^{35}\) LHS objects other than those using Hiragana, are displayed in serif font. The letter \( r \) has the mnemonic: ‘relation’.

\(^{36}\) We’ve built this so that \( R \) itself is a category. This is essential if we wish to evolve this system to an introspective intelligent agent system that can grow new insights.

\(^{37}\) This and the previous principle are tantalizingly close to notation developed as Feynman Diagrams which require virtual particles (Pukhov et al., 1999). We leverage this analogy in one of our studies for apt user interface metaphors, the so-called bowtie.

\(^{38}\) A simple example is how our subject will recall her romance, narrativising it for herself. She will have one ontological cluster for romance in general, and another for her romance, much of which is drawn from the general cluster of ideas regarding romance, as well as some situations governed by it.
4.16. Guided interlayer morphisms and experimental iteration

Now we take advantage of the harmonized nature of the RHS layers.

Using our persistent transformative linkages through the LHS, we can morph from one layer to another. It is a lossy morphism going \( \text{LHS} \rightarrow \text{RHS} \), but being able to express the new insights in terms of molecular dynamics is extremely useful to biomedical researchers.

To support this, we will have pulled out a subset of \( R \) that is just for morphing between layers. Due to the way it captures the flow of information, the dynamics of \( R \) are applicable to any domain. Still, that subset of layer-to-layer morphing must be domain-specific, even application-specific, because the emergent insights will vary from problem to problem, even within microbiology. For instance, in our example case we have even closer coupling within layers:

- molecular interactions can be zoomed to reveal (insofar as we know) the energy functions driving the geometry.
- our generic information flow relations (again, insofar as we know) can be zoomed into neural and chemical signals.
- our internal narratives can be zoomed into constituent emotions, memories and desires.

In this translation, new connectives will appear in the form of our \( < \) functions. These can be translated as ‘possibly could cause’ and similar statements, depending on the needs of the researcher. These, then would be indicators for experiments. The results would be fed back in as new knowledge, which in turn can modify every link in the system.

4.17. The dynamics modeling tool

We have designed some modeling applications to assist this work. Though there are already mature user interface vocabularies for presenting and interacting with RHS facts, we as a community have no user interface conventions for visualizing and interacting with the soft objects on the LHS. So while designing the approach, we had to concurrently invent user interface conventions. One is a dynamics modeling tool. The utility of this format is to allow an expert modeler to review known RHS expressions and decompose them using situated reasoning and related narrative principles. The purpose is to identify the LHS dynamics in play, thus populating an initial corpus of LHS objects and morphisms. The tool is designed by Beth Cardier and described in some detail in Cardier (2012). We start this section with it.

The second we call the cube tool, because it features six perspectives, each on the face of a cube, most of them exploiting the depth of the solid. This tool can subsume the other two (the Cardier-designed tool and one called the bowtie). It was conceived in workshops with Ted Goranson and Matt Garcia. This cube tool would be used in domains where a robust LHS universe has been described, using the dynamics modeling tool.

The purpose of the cube tool is to allow a modeler to explore the LHS and manipulate LHS structures to see their effect on the RHS. With some skill, a scientist should be able to find new insights into causal mechanisms, design experiments to test those insights and express the validated results in terms of an information flow theory, expressed in RHS terms.

The cube provides several integrated views. The third user interface paradigm, the bowtie tool, elaborates on one of these views to allow a more focused analysis of situations, rather than on...
Some elements are common among all three frameworks (and among all views on the cube):

- All share a common element inspector that shows the information about an object in the various possible representations (natural language, infons/logic, and some code-specific representations).
- All share a common view of the ontology graph. A user can transition from one tool to another via this view.
- Menus, gestures, spatial navigation and so forth are shared.
- The internal model is the same.

As mentioned, our example assumes that our source biomedical information is encoded according to the standards intended for the (US) National Center for Biomedical Ontology, following the guidelines of the Open Biomedical Ontologies, which in the future will be encoded using OWL 2. OWL is the ontology standard for the so-called semantic web.

This corpus is therefore available to us as Resource Description Framework triples, in the form of subject-predicate-object expressions. Our infons are displayed as predicate; subject; object expressions, so mapping from RDF to infons is possible. Such mapping allows us to take advantage of the OWL Description Logic (as RDF Schema) (W3C, 2009), which is currently the most mature ontological framework.

In the example, we assume the use of other already-established corpus databases. Our example uses information guided by the Gene Ontology (http://www.geneontology.org), and specifically their biological process domain ontology, wherein the predicates are transformational functions, just as we prefer. We also assume access to appropriate integrated ontologies. These include:

- A growing list of conformal biomedical ontologies, at [http://obofoundry.org].
- A similar list of 600 non-biomedical ontologies that use Common Logic (an international standard and the central component of OWL) is at [http://stl.mie.utoronto.ca/colore/ontologies.html].
- Other international efforts are providing access to a larger set of ontologies; an example of a federated project is the Open Ontology Repository [http://ontolog.cim3.net/cgi-bin/wiki.pl?OpenOntologyRepository].

Fig. 15 shows a display of this kind of source information, as we model it on the RHS. When these boxes contain constituents, they function as a type of situation, the degree shown by curvature of the lower corners. This convention is used in the dynamics modeling tool and the concept lattice face of the cube.

Incoming information is displayed in this central field of our modeling tool. Each chunk of information is displayed in a box with the intuitive annotation displayed. If this were text of a natural language story, the box would contain the chunk of text itself. If a film, it would be the cinematic artifact with annotations. In the case of our example, the displayed text is the natural language description of the event, similar to what is shown in Fig. 3.

Boxes are composable and decomposable within ontological constraints so the modeler can work at the level of granularity she requires. Clicking on the lower part of a curved box opens the components (as shown in the figure). Clicking the blue globe icon shows the underlying RDF expression with a link to its source in the originally presented context, usually a simple database. Clicking the red infon chevrons shows the underlying infon which can be examined for details of the type system and < functions. Clicking on the triangle at the top of any box displays the ontology tree that is applicable at the current state. (Each infon’s ontology trees change as new infons appear, so to see a history, you would have to roll back the states using a slider — not shown.)

Fig. 16 shows a representative layered ontology. As the infons build a situation fabric, the ontology differentiates into nested layers. We require at least an enclosing layer, being what is normally considered the applicable world ontology, labeled in the figure: general ontology. We require at least a governing layer, being the most specific coherent ontology that applies to the narrative structure so far. In this figure it is apoptosis. The governing ontology presents the candidates for early nodes in the graph, satisfying an observed spooky effect in lexical assignment (Bruza et al., 2009).

---

39 Details of the semantic web ontology, OWL, and its resource description framework are not essential to understanding the framework. OWL is a standard; it has a lot of attention, is the most mature of all options and has been adopted by the biomedical community. The RDF format is merely a standard way to package data that can be assembled into a knowledge representation.

40 Substantial study has been performed regarding the nature of these annotations.
The description logic that is used in well-formed ontologies — like those we expect from the existing projects in our example — has two type spaces used for defining relations, called TBox and ABox. (A good reference for descriptive logics is (Baader et al., 2007) and a relationship to key biomedical ontologies is described in Wroe et al. (2003)).

TBox relations define underlying terminology whereas ABox relations describe assertions over the world. They can be seen as respectively defining general and specific worlds. Unfortunately, when used by others, these methods — when complexity is at the level of our example — produce system designs that are not practically fieldable. This is because of the depth and methods of evaluation required. This is the barrier that a researcher first encounters; even if she believes she can do everything with RHS methods, the cost becomes too high.

We mitigate this problem by building our layers dynamically from RHS conditions, consisting of nested clusters of ABoxes where each parent appears as a TBox to its child.41 Fig. 16 has general bodily functions as a TBox to the ABox of olfactory sensing functions, which is in turn a TBox to apoptotic functions, which itself appears as a TBox to the assertions in the infons. The < function in each infon arranges the ontological elements in this subsumptive hierarchy, moving some elements semantically closer to the graph builder and others farther away.42

The conventional course of events in the knowledge representation world is that some group of people creates a description logic; another group uses that to create an ontology; then a third group uses the ontology to reason about the represented world. In other words, once the description logic is specified, that is that; similarly, the supposition is that once a feature of the world is adequately modeled, that is done. An infon element in that case will always build the same ontological graph, regardless of context.

So far as the user is concerned, in our system we morph the ontology and tree-building rules for each local situation (and considering each state of the system as a different situation) as if we are morphing the description logic and the ontological rules.

Taking profiles of the situations and stored situation dynamics, the system morphs the ontology in fundamental ways. The effect is that at each instant, the ontology and description logic are different, and the ontology trees of every connected element (all the elements of every previous infon) adapt.

What we are doing at this step of the example is capturing and storing observable situation dynamics to later support this morphing.

Fig. 17 shows the zones of the core panel of this tool. The top zones are the layered ontology subsets (a situations) just described. We now add bottom layers which are where we place virtual situations that are created as the process proceeds. If the infons model the facts being delivered to a human (or human-like machine) then this can be directly mapped to internal cognitive groups.

In this tool, rounded rectangles (plus the ontology layers) are these dynamic situation groupings. Different colors and location are used to denote different characteristics of the groups and roles they play in the morphing. Rounded rectangles contain elements that define their influence. Rounded rectangles may be very shortlived, or persist in the interpretation.

Double ‘funnel’ lines denote active morphisms; single lines model relevant past ones. An example of a model underway is shown in Fig. 18. (This tool is fully described in Cardier (2012).)

This first tool is designed with several modules to complement the central panel shown. Fig. 19 shows one assembly of those modules. The upper left has a tool palette. In the center is our modeling region. On the upper right is the source information. The screenshot shows the fictional story described in Cardier (2012). In our example, this may be any account of the process including a technical paper or an automatically integrated lab notebook such as (Hina et al., 2011).

The lower right is a view of the dominant causal path of the concept lattice as a vector in the Hilbert space of the current state. Zooming it allows for haptic manipulation of that vector. Fig. 20 shows this module with some information from an intelligence application.

The lower center of the layout of Fig. 19 is used for a display of the bowtie stream, described later in its own context. You can see a slider (in this domain, called a scrubber) in the top of that area with a sequence of key frames of past (and in this case future) states so that the modeler can move back and forth among them.

The lower left panel is for a vertical sequence of views from the cube tool, also described below. This gives a sequence of the emerging causal lattices.

Returning now to the central panel, clicking on any object gives you the lattice possibilities for future causal influence, based on the expected morphisms. These are ranked and the most likely one is expanded in the center of the figure. This is shown in Fig. 21.

Note the handles on the right hand side of this center panel. These are drawers which the modeler can pull out. The main view only shows key elements of the ontology, and the drawer provides for more detail of that layer. A schematic of a high level view is shown in Fig. 21, again with significant colors and notation of the semantic distance and binding tension. Here again, only essential elements are shown Fig. 22.

The bowtie shaped slider to the right sets focus and changes the focus of the view. Another view (not shown in this paper) gives the entire ontology graph and supports detailed display of information about each element. This view, in contrast is skeumorphic and shows agency at high level. (Agency is an emphasized quality in this tool.)

The drawer is useful because so many existing ontologies are noun-centric, where our dynamics act on what would be considered verbs. So we often have definitions that would be difficult to fully evaluate if we couldn’t change the focus to objects and their qualities. In effect, this drawer imposes a different set of ontological layers. We compute this as a horizontal striation compared to the vertical striation of the common main view.

41 This problem is usually addressed by worrying about how to implement frames in the description logic. The OWL 2 specification does not use frames for related complexity reasons. Our trick is to get the effects we need by shifting the computational tasks to the RHS while still leveraging the advantages of the OWL 2 RDFS-described logic on the RHS.

42 The reader is reminded that this nesting and the ontological realignment that occurs is not done ahead of time, as is the case in modal logics. It happens in unpredicted ways on the fly. The layers emerge, in the sense that progressive, conditional interpretations of data create new reference structures.
This whole tool is used to capture LHS morphisms and virtual interstitial situations so that a base can be built of LHS dynamics from observed behavior.

4.18. The cube tool

A second tool is used by a different sort of expert, because it focuses on established RHS dynamics and maturing LHS dynamics. The user in this case will manipulate graphical models of structures on the LHS to see implications on the RHS. The goal is to make informed predictions of RHS behaviors based on the expanded perspectives provided by LHS dynamics. In the biomedical space, these constitute speculations that can be experimentally tested. On conclusion of the experiment, this tool or the dynamic model can be used to refine the LHS dynamics.

Some notions used by this tool have already been illustrated. We call it the cube because our implementation uses the metaphor of a three-dimensional cube, with different perspectives on different faces. A modeler can move back and forth between views to perceive additional structure, or unfold the cube, to lay it flat on a large screen or set of screens, and show how one graph is modified if another is manipulated.

One face shows the causal lattice of Figs. 10 and 12. Another shows the current ontological graph of selected elements to a user-selected depth. A third shows a view of a relevant LHS object with the features we will describe in a moment. A fourth deals with LHS patterns, what we have referred to as a LHS ontology. A face is dedicated to the morphisms related to LHS to RHS influence while the remaining face (the back) is for the user to toggle among a bowtie view, the Hilbert Space vectors or the dynamics panel described above.

Fig. 18 shows these faces unfolded.

The cube allows us to use the third dimension (the inside of the cube) to display additional information. For example, our causal lattice is a cartoon simplification of entangling dependencies among the ontology graphs of each element (including their infon assembly). An educated modeler may want to increase the metaphorical depth of focus behind a lattice or category view in order to see the nature of these entanglements. These can be seen in terms of the discrete semantics or as clouds where spatial proximity has an intuitive analog.

The analyst may wish to color or tag certain elements in the cloud to track how they change, perhaps indicating or tracking non-continuous behavior.

The primary use case for our example has the modeler working with a view of the LHS. You will recall that for each discrete instance of a structure on the RHS, there exists a discrete categoric object on the left, derived by morphing the logical topology from the RHS to the LHS. In our example, the RHS object is a skeletal category, a lattice, and the LHS object is its half-dual. (In many cases, we will choose more sophisticated objects.)
But we also have LHS objects that do not have this RHS provenance. They may be virtual situations that empower an elegant calculus of the dynamics. They may be situations with instances that are soft and unknown (or unknowable). Or they may be situations that contain fact sequences we would like to know. The presumption is that we can reach some of the latter via a talented exploration of the former.

Fig. 24 shows a schematic of a typical LHS object. It has several notable features in this view.

The outer ring distributes the nodes of the half-dual based on forces we will momentarily describe. The lines among those nodes are the same as in the initial diagram, exist as ‘arrows’ in the system and are implicated in the forces that structure the display on that outer ring.
Once upon a time there was a place where the big bad wolf was not feared. Instead, everybody and each other's name called his name, and he was known as the "Red Riding Hood" of the town. His behavior was friendly and peaceful, and he never caused any harm to anyone. All it wanted was to be left alone.

Now in a cottage near the town, lived a little girl who went by the name of Little Red Riding Hood. It was obviously an alias. She was a young girl, a bit precocious and an agent of information. Anybody could tell by one look at Little Red Riding Hood that she was full of intrigue, but she could also read minds with ease.

To a casual observer, perhaps, Little Red Riding Hood might seem just a pretty little ten-year-old child, but this was a superficial piece of character analysis. The kid was not to be trusted too much. She was a mischievous, a thinker and an interrogator. And on top of all that she was not interested in peace or a better world order.

Little Red Riding Hood had a grandmother who lived about two miles away. Grandmother was a "townie" and Red Riding Hood liked her. They never invited her any where.

It came to pass one day that the peace, happiness and togetherness took an abrupt and sudden turn. The wolf was not there, and the wolf was not there for a little while. When the wolf walked he liked to...
The inner ring shows another category, one drawn from the $\mathcal{Z}$-centric reference dynamics that apply on the LHS. There will be a coherent set of these and ‘placing’ a different one will produce a different topology of governance and hence a different geometric distribution.

In simple terms, a LHS modeler will be looking for missing pieces of the outer ring, and she will do so by experimenting with the influence of different categories in the inner ring, and by moving objects around on either ring (usually the outer one).

The tool for performing this operation is shown in Fig. 25 (one screen of the tool view). It uses an iPad as the touch input device for a workstation with a large display that is used in a darkened room. Experience shows that the situated display of very large sets is more manageable when seen as clusters of ‘stars’. The workstation is networked to databases and ontology servers from distributed locations.

The figure shows the half-dual in a three dimensional view, distributed on the top of a torus. This view can be swapped for the two-dimensional flat disk shown in the upper left. The figure shows an inspector/controls panel slid out from the left. Normally that window would be closed.

The central column is the integrated collection of the categories that model the system dynamics. The modeler selects a governing dynamic by sliding this ‘column’ up and down. It is a complex object which can be browsed independently, but whose description is beyond the scope of this paper. (Details about the tool can be found in Goranson (2012c).)

The nodes are color coded. When the modeler has created a structure that can be expressed in RHS infons, the color indicates the RHS type system that is accessible. For example, red ‘stars’ indicate that RHS expressions can be extracted that characterize the situation using the type system of structural biology.

Our agenda in the example has the initial object as one rather more complex than is pictured, encompassing the initial RHS expressions having to do with sensing, apoptotic refresh and romantic memory. The modeler seeks a symmetric arrangement of blue nodes that can be expressed as the emergent information flow model. From there, speculative expressions can be mapped to using red and white nodes. (White nodes are those without a known correct RHS expression.)

4.19. Grand challenges

An understanding of olfactory apoptosis can be the starting point for many related issues. Some that seem obvious are:

- Understanding how symbiotic bacteria in the nasal passage mediate resources in the immune system. We know there is some correlation. Insights into this mechanism could inform new immunization and therapeutic paths.
- Understanding system-initiated signals for controlling neural stem cells. We know that some mechanism mediates the signals from stem cells to granules, and possibly the ‘pump’ that carries and directs them through the stream. Insights into this system could allow for the possibility of general neuron replacement.
- Understanding mediating signals for creative apoptosis. We know that healthy systems control a balance in the replacement of fresh cells and that cancer cells are immune from apoptosis. The ability to model this in general terms could open the possibility of system-initiated healing by induced creative apoptosis.
- Understanding the relationships among possible quantum effects in scent capture at receptor cilia, and the mechanisms of information transfer, recognition and recall. We know that we can observe quantum-like effects at several stages from the initial cilia through chemical and electrical pathways. And we know that some cognitive functions show similar quantum-like effects. Though a coherent theory is unlikely to come directly from physics, some larger view may develop a biologically-sensitive quantum mechanics. This could inform next generation computing machines.
- Understanding the nature and purpose of the uniquely bicameral olfactory system. We know that the dominant nostril alternates throughout the day and that the two sides host slightly different sensor topologies. If we understood this and why, better insight into the connection between cognition and the autonomous nervous system could result.
Understanding how psychopaths lose their sense of smell (Mahmut and Stevenson, 2012), whether it is purely in the brain or distributed through the olfactory system. A deeper understanding of this may inform a new class of brain disorder diagnostics.

Studies such as these would be the target of future work.

5. Influences

Our work is interdisciplinary; rather than being a significant advance in any one discipline, the novelty in the synthesis of work by others into a coherent framework. This section briefly outlines the major influences; an intent is to demonstrate that though there is no direct precedent for the approach, it can be evaluated as having emerged from solid foundations.43

5.1. The Wigner-Von Neumann proposition

This work began under a program influenced by Wigner (1973), with the specific intent of following a challenge made by Birkhoff and Neumann (1936). The challenge — as communicated — was to map a suspected universe of geometric logics that includes quantum logics. Later, this was modified (von Neumann, 1966) to move from reliance on abstracting to Hilbert space — a strategy of mapping logics to vector space for algebraic benefit.

Wigner suggested that group theoretic abstractions could inform this effort, much as mathematics in general informs any scientific theory (Wigner, 1960) and specifically how quantum behavior in physics informs quantum logic and group theory informs the eight-fold way (Marx, 1996).

This early work of ours had two inflection points.

One was our encounter with Michael Leyton, who developed something very like an intuitionistic linear logic based on group theoretic operators in his process grammar (Leyton, 1999). Our work is informed by his work.44

The other major event was an impassioned informal talk given by Yuval Ne’eman at the meeting he hosted of the symmetry society mentioned below. In this talk, he championed the inherent geometric logic of the universe and suggested that furthering the task of exploring this structure, new mathematics beyond existing group theory might be required. (The corresponding, milder paper is (Ne’eman, 1999)).

---

43 The reader should not read a mention of any of these influences as an endorsement of our proposal.

44 Study of Leyton’s process grammar reveals a creative way to incorporate a representative of a virtual LHS in his domain-specific control groups.
So from the beginning, we knew that we were dealing with a metamathematics over linear logics, characterized by symmetry-controlled morphisms.

5.2. Barwise and Devlin

Our association with research supporting the US intelligence community provided new energy. Von Neumann not only suggested a larger world of logics; he warned that Aristotelian logic — though an effective basis for an initial generation of computing machines — was inherently incapable of reasoning about the open world (von Neumann, 1966): “it is true for all these automata that you can only assign them a value in combination with the milieu which they have to face... it is therefore quite possible that we are not too far from the limits of complication which can be achieved in artificial automata without really fundamental insights into a theory of information”.

Many practical analytical problems have been encountered in the intelligence world; that community can be characterized as the leading edge in practical machine reasoning: in scale, in attempts to understand human motives, and in ambitions of fidelity in prediction through models. Logic as it is commonly implemented just does not do the job. A good survey of the failings is described by Devlin (2009) quoting (Heuer, 2001).

As informed users, some in the intelligence research community created a market pull for (something like) this approach.

At the same time (the early eighties), the problem was widely recognized among mathematical logicians and cognitive scientists. In response, the Stanford Center for the Study of Logic and Information (CSLI) (CSLI, 2010) was established under Jon Barwise’ leadership. That Center produced work that resulted in situation theory (Barwise and Perry, 1983). It is a well founded framework for two-sorted reasoning, inspired by model theory (Chang and Keisler, 1990).\(^45\)

Subsequently, Keith Devlin extended situation theory (Devlin, 1995) by adding a type system to infs, developing a zooming technique where referenced situations can optionally be explored and defining a practical vocabulary of constants and constraints. The primary value of this work was in making the two-sorted approach generally practical. (Devlin’s work is formal, but can be judged as a philosophical framework for human reasoning rather than a directly implementable computer architecture.)

Simultaneously, Jon Barwise extended situation theory in another way, changing from a focus on information modeling to information conveyance. He called the result channel theory (Barwise and Seligman, 2008).

His second sort was concerned with characterizing the situation of the communication medium, which is relevant to the work described here as the inspiration of our information flow model. The value for us is the way Barwise explored categories to model coherent concept structures in the second sort. The technique of set theoretic logic in one sort (on the RHS) and category theoretic logic in the second is not new, but it was new in the context of situations and the pre-existing, mature framework of situation theory.

We often present our approach as situation theory with loosely coupled categoric abstractions on the left hand side, and which have internal narrative coherence.

5.3. Categoric abstraction

We work with categories in the second sort, drawing from two foundations, one in computer science and the other — related — in logic.

A primary influence is the practical advantage categories give an implementer concerned with computation. We want practical tools, what the Biomathics community describes as computable. The logic of any computing program is characterized as categories; it is a fair statement to say that the science in computer science depends on category theory applied in this way (Pierce, 1991).

Categories cut the other way as well. Based on a well known theorem (Sørensen and Urzyczyn, 2006), any well formed categoric set of functions can be translated into executable code. This is known as the ‘morphology’ of the logic to be expressed categorically (Kontchakov et al., 2008).

Almost always this technique is applied to build a universe of categories that are derived from the right RHS. In these cases, the goal is to get another analytical handle on the right hand side, keeping the one-sort rather than building a second.

One thing we add to this is an implicit component (our <) in right hand side infs that can be used as a category theory abstractions. In right hand side infs, such that when extracting the topology, the left hand side is a true second sort — a quite different beast than categories that retain the same limitations of the original abstractions.

In practice, it makes sense to use the simplest constructs possible, depending on the demands of the science and the infelibility of the domain. The mathematics of p- and o-categories is of interest here, because it gives us a ready zoology of category types to use.

The examples we give here use very simple options because an information theory inspired by biology does not have to accommodate introspection, delusion, irony, lying and such. Depending on goals and domains, other work may have to use more complex mathematical objects on our LHS.\(^47\)

Much of the mathematical thinking in our current implementation (Goranson et al., 2012) comes from insights from Matt Garcia.

5.4. Focused collaborative groups

This work draws heavily from many disciplines, and has benefitted from exposure to some advanced thinkers in interdisciplinary groups. We participate in three fora that have provided useful context. In this section, we briefly mention the groups and their bearing on this work.

The International Society for the Interdisciplinary Study of Symmetry. This group was established in the mideighties, headquartered in Budapest. Founding members include esteemed

---

\(^{45}\) Model theory originated as a mathematics for interpreting formal languages, but in the present context can be described as the foundation for mathematical systems that reason about (other) mathematical systems. An example may be theorem provers where the mathematical logic used in the proof needs some careful bookkeeping compared to the mathematics being examined.

\(^{46}\) This paper does not describe the implementations in code, though it is as important that the models be efficiently computable as it is that they apply to real (biomedical) problems. Purely functional languages are not used in the mainstream, but some commonly used languages support the functional programming model to the extent this approach assumes.

\(^{47}\) For example, see (Döring, 2011) for a topos-based approach.
minds and the membership has spanned several hundred. The interests vary widely, but among the society's journals are some important papers. Our project maintains this corpus as an on-line resource (Goranson, 2012b).

In this forum, Husimi et al. (1991) and Ogawa (2000) were influential in describing different group theoretic linear process logics that have behavioral coherence applicable to LHS dynamics. Takaki (2004) has provided senior guidance on a user interface project that parallels the work described here.

Husimi, Ogawa and Takaki were (successively) leaders in a group studying katchi in science, a concept very much in tune with our LHS (Various, 2012c) (http://katchi-jp.com) and which informs our ϕ dynamics.

The aforementioned talk by Yuval Ne’eman was for the Society’s congress in 1998 which he cohosted (with Dan Shechtman). Foundations of Information Science. This informal but long-lived group is administered from Spain by Marijuán (1996), cofounded with the late Michael Conrad (Parlee, 2002) and Koichiro Matsuno. Matsuno’s ideas are outlined in a later section. A theme of the group is from Conrad: “The goal is to understand the dynamics of natural evolutionary systems and to use the principles to design computing systems with adaptive capabilities”. (Diebner, 2002). These theories will model emergent properties and are a contribution toward a new foundation for (and definition of) information science.

FIS primarily works as an email discussion group, and often strays from its original vision. But some powerful thinkers have had opportunity to explore some notions in more detail and with more probing than supported in a journal or a conventional forum. The dialog in the FIS forums from our perspective has been enormously useful and some of it has influenced this work.

Jerry L. H. Chandler in particular has worked from first principles, building a notation for biochemical structure that incorporates accretive structure, something that could be characterized as Leytonian mechanics applied to protein structure. This, or something like it, will be necessary for better RHS expressions at the molecular layer. (A representative email is (Chandler, 2011)).

John Collier is a philosopher who is active here, and has done essential work in relating foundations from C. S. Peirce to this larger context (Ladyman et al., 2009).

Active members also include Stanley Salte and Koichiro Matsuno whose contributions are noted below in more detail than this section allows.

Quantum Interaction, an annual workshop, is the third community of interest. This meeting follows directly on the von Neumann challenge to comprehend a quantum logic or logics. There is no specific coherence to the work of the attendees other than the portability of quantum logic (whatever it is presumed to be) outside of the domain of quantum physics.

The workshop series is characterized as quantum logic without physics. There are far fewer encounters and papers than with the other two groups, but some more concentrated relevance is apparent (Various, 2012b) (http://www.quantuminteraction.org). Co-organizer Peter Bruza of Queensland University of Technology represents that some textual information conveyance has quantum-like properties and quantum-logical techniques can improve data retrieval and related tasks (Kittö et al., 2012).

Widdows (2004) and van Rijsbergen (2001) have similar views. A useful lesson from this group is the divergence from the original framing of the problem by von Neumann and those that followed. The legacy approach abstracted first into algebraic space — originally Hilbert space — and then as a second matter into the application domain. Abramsky and Coecke reverse this order and apparently avoid a lossy abstraction problem and make some progress after decades of relative failures by others.

In related work, the Quantum Group in Oxford’s Department of Computer Science is run by Saul Abramsky with Bob Coecke. The interesting work here is purely categoric quantum mechanics. Their application is not so interesting to us, because they are focused on ordinary quantum mechanics as applied to physics. But the formal explorations of (so-called) geometric logics and categories is immensely useful (Abramsky and Coecke, 2004). It directly relates to the stage Barwise’ work had reached when he died, and underscores that conventional logic and settled conventions in physics aren’t ideal even for physics.

Dusko Pavlovic (Coecke and Pavlovic, 2007) in that group works on applications in functional languages that apply to computational problems like trust and security. These may inform coding strategies.

(A useful lesson from this group is the divergence from the original framing of the problem by von Neumann and those that followed. The legacy approach abstracted first into algebraic space — originally Hilbert space — and then as a second matter into the application domain. Abramsky and Coecke reverse this order and apparently avoid a lossy abstraction problem and make some progress after decades of relative failures by others.)

Also in the Quantum Interaction Symposium group, Hiley et al. (2002) reports on the work he started with David Bohm on understanding implications of what they term implicit order. We map something like this notion directly to the coherent dynamics of our LHS categories.

We believe that all three of these gatherings will reward a participant interested in Biomathics.

6. The approach compared to others

Earlier, we noted that this approach supplements others rather than replacing existing methods based on legacy abstractions. While we believe that some RHS abstractions can be more naturally rooted than others, a key principle is that the overall model and its abstractions should be tailored to the problem. We suggest that a categoric second sort derived from situation theory can integrate with other RHS methods to address system dynamics.

In this section, we compare the proposed approach to a few other methods. The goal is not to provide an exhaustive survey, but to provide some illustrative examples.

Rather than reproduce a description of the theories as their proponents would, we attempt here to express the key concepts in terms we have established here. In all cases, we believe these
approaches to be promising enhancements to RHS mechanisms and (probably) compatible with our proposal.

6.1. Ehresmann: memory evolutive systems

In Ehresmann and Vanbremeersch (2007) Andrée Ehresmann outlines an approach to model emergent system behavior she calls Memory Evolutive Systems. It is designed to be applicable to general problems but has been most exercised to model concepts (as memory objects) and their relationship to neurons.

Her proposal accepts the existing representations of neurons and their interactions, plus what dynamics are experimentally known at this layer. The theory also assumes that concepts that are dynamically self-assembled from components are best modeled as categories with time-stepped dynamics as functors; we make the same assumptions, as do the aforementioned Abramsky, Barwise, Bruza, Pavlovic, Wigner and others.

The meat of the theory is in bridging the two (neuron-layer dynamics and memory) with a collection of (what we will call) vertical connectives. The payoff is the resulting vocabulary of interrelated categories that model multilayered dynamics and imperatives. This is a much richer model than that proposed by Rosen (2005) which has — in this context — only one layer.

Though there is no explicit intent in MES to introduce a second sort, it seems that the $< 2$ function can be completely described with MES operators, and the notion of a single situation, which is to say part of $< 1$. But there seems no way to support the quantum-like reinterpretation of the past and strange couplings which we capture in our $< 3$.

6.2. Kauffman: complexity theory

A common notion in many of these models is that relatively small components can interact to produce systems that have higher level behavior. This system-level behavior is considered to have emerged.

Kauffman and colleagues (Kauffman, 1996) imply that all of the necessary properties for the emergent behavior is held at the atomic layer. Thus, instead of a mechanism like ours and Ehresmann’s where two possibly diverse ontological systems are unified, so called complexity theories hold that the new ontological definitions of the system are a direct projection of a latent quality of the constituents.

Thus, emergent mechanisms are often proposed that are based on arithmetic and probabilistic principles. The presumption is that interactions are simple; many emergent attempts fail, and those that succeed do so because of retrospectively identifiable properties of the components, which are also simple in a set theoretic sense.

The interactions instead are assumed to be complex in their number, variety and behavior, with some general principles carrying across domains, for instance from economics, protein behavior and neurophysiology. Though ‘complex,’ the principles are traceable and expressible in the ontology native to the layer or domain in which they occur. This comports well with conventional models of evolution where simple systems pre-exist complex ones historically.54

However, such an approach does not acknowledge that when systems interrelate, additional dynamics might be present. Matching such models to experimental findings is relatively easy after the fact, just as explaining stock market behavior is — after the fact. The basic concepts have some elegance because they are simple and always easily within computational reach.55

The problem is that probabilistic models are semantically lossy. We assume that when information is conveyed, at least in biological systems the nature of the message in the signal is significant. Quantitative arithmetic and related probabilistic networks are not able to take these details into account, in the projections that are supposed to emerge from them. In other words, if we are dealing with information in the system, we have to work with semantics (or some equivalent) rather than flattening to numbers.

We could characterize the structural dynamics at our first layer using these techniques, and some do (Kauffman and Levin, 1987). If we encounter practitioners who find this useful, we believe we can accommodate. But there is no analog for the other two layers (information flow and natural language-related concepts), so the morphism among LHS objects would likely be less rich.56

6.3. Salthe: information entropy

Stanley Salthe takes a quite different approach in stepping from physics to biology and other domains (Salthe, 1989). He preserves the notions of conservation and thermodynamics but shifts the focus from objects, fields and forces to information.

So, following a direction generally indicated by Prigogine and Hiebert (1982), he can build a theory of emergent system behavior based on increased local information structure. Information of the system thus occupies the same ontological domain as information about the system, and thus becomes more malleable as a core abstraction.

This has distinct advantages in leveraging some core principles in physics, while cordoning off others. Any number of techniques that structure information — according to the entropic notions — can be enfolded. Our strategy is to worry first about abstractions, and Salte is on the same page.

This could be an attractive approach for structural biologists to take in forming infon relations, and our suggestions in the example are informed by this. The work by Salthe and colleagues is very well developed at this end, and then there is a relatively vague assertion that whatever works in physics would similarly work in biology. We may be able to populate these dynamics.

6.4. Matsuno: molecular tense

Matsuno (2002) can be said to have gone even further in how what we normally accept in physics is rethought in biology (at least biology, but likely other domains).

Foundation concepts in physics are force and object, which are combined via quantum mechanisms and expressed as fields (and their related, resulting particles). Following some experimental evidence, Matsuno shifts fundamentals, so that time is more fundamental than force. This is to say that if we decompose force — which is what mainstream structural biology is all about — then abstractions of time are primitives.

Matsuno then develops a proposal that more useful abstractions in biology will include tense. Since he interprets physics as necessitating a force-time dependence, this is consistent with physics. He

54 The paper by Gabora in this issue uses mechanisms representative of this approach.
55 Murray Gell-Mann noted an implicit assumption in this, that the supposed mathematics — meaning in his case arithmetic and probability — of the universe has the happy coincidence of perfectly matching the mathematics that are handy for both machine manipulation and human comprehension. This was a matter of private disagreement with Wigner that mathematical rather than intuitive elegance was superior.
56 This speculation is informed by a similar problem with Bayesian emergence in the intelligence domain.
has not yet published a workable framework for these abstractions beyond describing the dependence of the present progressive tense (what is being caused to happen) on the present perfect tense (what happened, with a peculiar and subtle interpretative connection).

We should note that this is quite different than noting state, which is a property of objects in a system; rather, it abstracts something akin to intent. We use a comparatively clumsy metaphor of shifting from nouns of ‘object, force and state’ to verb-like abstractions, but the idea is the same. This is the best way to separate out the observer, being at the most primitive level of abstractions. We believe it to be a powerful strategy and possibly the best approach to what is being called biosemiotics.

Matsuno’s work is independent of ours, but he influenced our LHS type system where tense and symmetry are more fundamental than time and reification.

6.5. Integrating abstractions

All of these examples and others not mentioned can integrate with our proposal of some of them in concert — each serving to improve RHS models over current methods. The techniques described here were selected because of a history with INBIOSA, but we could have easily listed many others.

The central point is that any reasonably well behaved RHS works with our approach.

7. Biomathics

Generally we support the ‘Biomathics’ concept as defined by the INBIOSA project.57

7.1. The agenda

The basic problem, as defined in the editorial of Simeonov et al. (2012a), is that living systems are not well modeled by abstractions borrowed from physics — often conflated to Newtonian physics — and that some radical addition to the vocabulary of abstractions is required. We take this notion seriously.

Generally, those working in this area focus on one or more concepts of emergence, supposing that primary dynamics can be assigned to the low level components of a system such that they carry properties beyond those that govern their local behavior. These properties would operate collectively, perhaps at some threshold of complexity to produce emerged system behavior.

The cited volume collects diverse theories along these lines. This comports well with common notions of evolution where simpler systems develop into complex ones, and high level behavior is hierarchically decomposable as collaboration of low level processes. Various theories from this perspective sometimes make a convincing case that they are not ‘reductionist’.58

Using our terminology, most of these proposals stay on the RHS and devise nesting strategies, usually with derived, higher level type systems. We think a slightly different approach is warranted. The first parts of the INBIOSA White Paper (Simeonov et al., 2012b) defines two specific challenges.

The first challenge is “to design an original general system of abstractions within the biological domain”. We believe that to fully address this challenge we need an entirely different second sort of logic, empowered by our LHS (or something similar). You simply cannot have a revolution without new abstractions and new abstractions require a new calculus.

We further believe this cannot be satisfied by merely defining the complex and pushing dynamics into higher RHS levels. Our LHS dynamics include aspects not accounted for in current models (Cardier, 2012). These include: the relationship between multiple, ontologically diverse situations; situations whose foundations are in transition; a governing relationship between situations, where one will influence others so they adapt to its associative priorities; and, the identification of causal agents using the integration of multiple perceptive stances rather than objective determination. These behaviors have been observed in the higher-level information structures that drive stories, and in nature generally.

That is to say, the challenge cannot be addressed by abstractions that are rehashes of those from physics — even those from quantum field theory — however redefined. Nor do we believe that more novel repairs to logic can suffice, for instance complicating strategies such as modal (Zinser, 2007) and non-monotonic logics (Kaplan et al., 2008).

The INBIOSA investigators suppose that these higher level principles will be ‘inspired’ by (biological) living systems.59 We prefer to think that a useful framework will accommodate biological systems at simultaneous layers in ways that seem natural, so as to give the appearance of being ‘inspired’.60 A theorist should be able to capture notions of ‘emergence’ if she wishes, but not be necessarily so constrained.

We agree with at least the early parts of the INBIOSA White Paper that what results should be applicable generally across many domains and with computable frameworks.

The second INBIOSA-defined biomathics challenge corresponds to our program noted early in this paper: to apply any proposed ideas against real problems, including hard problems in biology. This effectively means addressing the grand challenges of medical research.

Either utility is demonstrated or it is not; nothing else matters, regardless of apparent mathematical or philosophical elegance, regardless of the attractiveness of a metaphor... and regardless of the popularity of computational techniques, because these are largely artifacts of the order of invention the constraints of our machines.

We share the expectations of many in the Biomathics community that significant benefits can result, and that those benefits are within reach. We also believe that the dynamics that will be revealed in this process are those we generally associate with living systems, and in some fashion one could say that biology ‘inspires’ new methods.

We differ in rejecting an implicitly assumed necessary allegiance to causality solely from the (low level) physical components. A common analogy those in the field use is termite colonies. Individual termites exist; colonies are an abstract notion, so any behavior that can be ascribed to the colony can be attributed to some latent properties of termites that emerge when collected.

57 INtegraL BIOMathics Support Action: Grant number 269961 of the Future and Emerging Technologies (FET) programme within the ICT theme of the Seventh Framework Programme for Research of the European Commission.
58 We have no problem with a reductionist agenda per se. Our goal is to reduce reductionism and channel the necessary decompositions to useful abstract primitives.
59 We handle this notion the same way we do the von Neumann speculations of quantum logic. Instead of assuming that quantum physics inspires a new logic, he suggested that there were a class of new logics with the logic of quantum physics one instance. We suggest that there are a class of abstract dynamics for higher level system/situation behaviors and those we observe in biological systems are instances of this class.
60 The phrasing of the challenge in this special issue (“Can biology create a profoundly new mathematics and computation?”) is unfortunately stated, but generally we endorse the INBIOSA agenda.
There is some handy arithmetic that goes with this notion of emergence, generally supported by work at the Sante Fe Institute.

Instead, we support that view (emergence from latent properties of components) as one intuitive metaphoric framework, but it should be just as valid — even if the history of evolutionary stages differ — to go the other way. Termites do not and effectively cannot exist as individuals, any more than a liver cell or a liver can exist without its host systems. We should have conceptually reversibly equivalence between systems modeled using the new Biomathics with their components, and the models using the new Biomathics appearing from properly aggregated components, as we noted in Fig. 1.

Therefore, a differentiator between our work and that of many in the INBIOSA community is the philosophical stance of where the emergent behavior resides. We have two parallel reasoning systems, the effect of which is that we can choose where to place our emergent dynamics. Others are forced into a descriptive type system that presumes that the way we (as human scientists) think about a system is the way that system ‘thinks’ about itself.

This type impedance can be (mostly) hidden in physics, but is unavoidable in the science of biological life, when there is some level of systemic sophistication. When the focus is on emergent behavior of bio-physical systems, this is a heavy burden for the theorist, one we avoid.

7.2. Questions about LHS reality

This paper presents our work in the context of useful tools and working from existing knowledge. However, many in the Biomathics community have approached the problem from different angles. Some of these, reasonably enough, concern the nature of reality distinct from models of specific phenomenon.

Earlier, we noted that the LHS dynamics will contain actors that are virtual, without any direct counterpart in the observed phenomenon. So a question arises, (slightly paraphrased):

“The partition of the dynamic into object/logic-centric expressions (RHS) and situational expressions (LHS) has been taken as model-dependent. The resulting models would reasonably be comprehensible if one tries to model biological phenomena currently available to us. However, if the proposed two-sorted logic can be naturalized, the evolutionary emergence of LHS must have been seriously considered in the development of the LHS dynamics. Is it possible to achieve a robust enough set of LHS expressions to form a robust, workable theory of the origins of life?”

The LHS dynamics are intended to evolve into an executable model of the way life works. This includes fully representing emergent behavior beyond the horizon, either in time or in contemporary dynamics that are unobservable.

A careful distinction has been made in this work between a model and a representation. We define a representation as an expression that captures observed measurements and faithfully emulates those measured behaviors when rerun. Most biology is representation-based. Our RHS when severed from the two-sort is a representation only, and indeed the representation that is normally used by us is that used in common practice. The best it can do is track and correlate measurements.

A model, in our consideration, is different, being a faithful replication of the essential underlying features and dynamics of the original.61 Supposing such a model can be hosted in an execution environment, it can be for all intents a parallel reality. Such a model employs the same causal dynamics as the original.

Our combined set of LHS dynamics, RHS expressions and LHS-RHS situated expressions we believe, if duly instanced, can be such a model. So yes, a scientist should be able to reverse the emergent behavior in time to various earlier stages in the emergence of life. Such a scientist in that case will only be able to virtually observe RHS-expressible phenomenon, even though invisible driving forces may be more prominent in these early stages of life.

This is only slightly different than the intended use as described in the paper, to exercise the model forward in time, rather than backwards, to make insightful predictions to test.

A further paraphrased question is: “The choice of apoptosis as an example seems a way of appreciating the importance of the natural process of replacement. Robert Rosen called this the process of repair. If this was intended, would that process (of replacement) when seen from the LHS be completely naturalized in the sense of being independent of the original, modeled behavior?”

Early in the paper, we credited Rosen with an eloquent statement of the problems with current biological abstractions. And we noted that his proposal to think in terms of category-expressed structure was apt.

But at the same time, we remarked that his proposed categoric structure is still captive to a RHS and thus cannot capture the implied observer in the process of modeling. This limit is apparent in the question where the observed phenomenon would be one of apoptotic replacement and Rosen’s abstraction would have to be a ‘naturalized repair.’ We have a broader mechanism that subsumes this where the impetus for the observed replacement is driven by an integrated group of RHS objects that meet Rosen’s challenge and which are fully naturalized (in this sense). But these RHS objects and the manner in which they influence behavior are not as intuitively comprehensible as Rosen and the poser of the question would have.

The reason is that in moving from RHS to LHS, we move into what we consider the abstractions of universal emergent dynamics. The example was chosen to highlight this difference.

A final question (not paraphrased in this case): “If one appreciates the class identity of individual material elements whatever they may be, the natural transference from the individual identity to the class identity of each participating material element may look like an abstraction. Do the authors accept the abstraction exclusively of material origin?”

The question assumes an equivalence that is not present in the proposed approach. The assumption in the question is that for a RHS object, class or behavior in the material world, there is an equivalent LHS abstraction. The mathematical logic used does not work this way. For every such object, class or behavior on the RHS, there is a dynamically coupled universe of transforms on the LHS. One could for certain purposes clump these LHS morphisms and categories into RHS expressions, as we have done with our information flow RHS expressions. But this is a lossy expression because of the soft nature of the LHS and the open set of its elements.

The question is best answered not in terms of whether there are Platonic abstractions on the RHS for classes on the RHS. Instead, we maintain that the abstractions on the LHS are indeed definitionally decoupled from the RHS and have — for the questioner’s purpose — a similar nature as Platonic ideals.62 The methodology in the paper could give the impression that all RHS objects and relationships are defined by material observation, but that is merely a starting point for registering LHS dynamics. This is why we stress

61 In some relevant literature, the definitions of model and representation have the opposite meanings.

62 See (Ladyman et al., 2005) for some philosophical perspective on this.
the importance of a skilled theorist and profoundly capable visualization tools.

Yes, the LHS can be said (in the context of the question) to exist wholly and in any part, independent of the material world. But the distinction is moot in our précis, which is that of ordinary science: to better understand, predict and engineer the behavior of systems, in this case living systems.

7.3. More questions

- What is our stance on reductionism?

  It doesn't matter much to us, though many in the Biomathics community worry about it and related concerns. Our overall strategy is to carefully engineer the underlying abstractions to produce a system that better models reality while being machine-friendly. In the usual case, such an ordered approach is not attempted and workers follow rules of thumb informed by philosophical insights. One such rule of thumb is that reductionism is undesirable and should be minimized.

  Reductionism in a two-sorted system generally has no useful meaning, except that if desired, each side can (informally be said to) be less reductionist than otherwise.

  Instead of following any rules of thumb, we strive to work from first principles.

- What is the relationship between your ‘layers’ and the usual notion of system hierarchies?

  The limits of natural language work against us here. Throughout, we have carefully used the notion of ‘layer’ rather than ‘level.’ Perhaps ‘domain’ or ‘world’ — terms common to knowledge representation — would be more apt. As our target audience is biomedical researchers, we elected to use the term ‘layer’ to reflect a higher degree of introspection.

  The difficulty comes from the intuition that there is a hierarchy of systems in life, with molecules (or something small and ‘simple’) at the lowest level and humans, societies or something physically large and complex at the top.

  Physical assembly argues for this, and as we have mentioned so does the intuition that complex animals evolve (emerge) from simple ones. We don’t feel it necessary to argue here that this is not useful, but we do think it needlessly distracting. In any case, the approach does not use a notion of subsumptive hierarchical levels. The discussion associated with Fig. 1 is intended to dispel that notion.

  That said, if a client community wants to build levels on the RHS to meet some practical need, we have no problem.63

- Does the approach necessitate a position on quantum mechanics and logic?

  No.

  We mention quantum logic in two contexts: historical and for applicability.

  The historical context is the modern view of the von Neumann speculations that we have described as supposing the world to be governed by a class of ‘quantum’ logics with categoric symmetries. This is not how he would have described it, but it is how it was delivered to us early in the program. We mention it because the provenance of the inquiry may help a reader place the described ideas in time.

  The second reason is rooted in application. Our exposure to the Quantum Interaction group reinforces the insight that many phenomena in life have quantum-like behaviors. With our two-sorted system, we have to accommodate the use of ‘ordinary’ logics on the RHS. But at the same time, it seems wise to anticipate what are likely to be breakthroughs in the creation of what we call ‘geometric logics’ on the RHS in the future — those that might better model real-world RHS facts.

  The section on work of others indicates some of these. Fortunately, the major trend in exploring ‘quantum logics’ uses a categorical approach that can be reconciled with ours. We neither depend on these for our framework, nor do we here make any specific proposal on what they may look like.

- What is the relationship to the work of Girard’s geometry of interaction?

  We do not use it in the approach as described. (The reader can understand Girard’s work, most recently in Girard (2011), as a well-examined formal framework to perform some of what we do by applying algebraic methods over suitably defined linear logics.)

  We made a deliberate decision to go with the foundations of formal concept analysis instead of Girard’s work for two reasons. The first is practical: we will be working with ontologies that already exist, and be using ontology formalisms (OWL 2) that are widely adopted. Description logics, conceptual structures and concept lattices are well integrated in the formal concept analysis community, so as a practical matter concept lattices lead to a cleaner implementation.

  In particular, (causal) concept lattices provide a leveragable user interface metaphor, and a library of ready, trustable tools. But we would have not used Girard’s work in any case because of the insight noted in the discussion of Abramsky’s work.

  A difficulty in the past has been the eminence of the abstraction architecture. The tradition, used by von Neumann and countless others is to move the world into an algebraic space first, and only then consider the problems of abstraction and types. Girard follows this pattern.

  The Abramsky insight (and our senior guidance from earlier) is to perform the tasks of architecting the abstraction space first and only then look for the most elegant mathematical structures and tools.

- Why not use a polymorphic typed lambda calculus, and its categorical semantics?

  Because we want things to work. Properly.

8. The research agenda

In our introduction we positioned our work as a proposal for tools to advance the science of information. With this in mind, the first research task should be picking what — before the recent irrelevance of the originating agency — used to be called ARPA-hard problems. These are problems that elude current methods, our brightest minds and in many cases massive funding. They need revolutionary tools and if solved ideally will result in some significant benefit.

We have proposed perception-influenced olfactory neural fabric realignment via apoptosis as a phenomenon of interest because it is fundamental, probably relevant to many therapies and eludes

63 Strictly speaking, our accommodation of a ‘signal’ as a collection of molecular dynamics can be seen as a hierarchy of sorts, as could our adoption of Devlin’s zooming. But these are far from the complex hierarchies invented to support emergent behavior.
comprehension at an emergent system level. But any ARPA-hard problem in biology would do.

In agreeing with the INBIOSA challenges, we believe that a first task is finding the right set of abstractions. In terms of modeling the interaction between systems as well as their components. This means simultaneously working on the LHS and RHS. The RHS conventions will be largely constrained by whatever lab we collaborate with. A goal is to let current researchers use whatever tools they think best suits their needs, and also to support whatever RHS improvements that appear.

The LHS abstractions are dependent on this and involve discovering details of the domain’s type system. Because we will be working in categoric space, this notion of type differs from the usual convention in ontologies. (That is to say, we need types outside the categories, not inside.)

We then need a vocabulary of common instances of those types where they exist, and a simple set of visualization tools. We also need a workable mapping of these types to correlated programming code objects.

Our example outlines a proposed approach to this.

The second task is a matter of clinical fieldwork. What we are creating is a framework for capturing observed LHS behavior. There is no reason to not treat this the way we would any scientific endeavor: to cleanly model what we observe, then to predict and test the theories against experiment. The objective is to build a system that provides new insights into the dynamics of living systems.

9. Conclusions

When we designed this paper, we worked a balance among: reviewing the background, making the case for something like INBIOSA, describing the mathematics to non-mathematicians (assuming biomedical theorists to be the target audience), and rooting it in a way that one can envision real tools, not just that can be fielded on a machine, but that can be usefully employed. We knew that even at this length, we would make many specialists unhappy that we did not anchor the paper in their world.

Our goal is not to convince others working in the field; Bio-mathics is a contentious and broadly competitive intellectual economy. Instead, our strategy is to build tools that do powerful things. The paper, then, is designed to describe that methodology.

The theme of the special issue is: Can Biology Create a Profoundly New Mathematics and Computation? We address the theme in a qualified manner. There is a demonstrable need for better abstractions in certain scientific domains, including system-wide microbiology. In addition to being a desirable application domain, apparently natural biological systems can provide a model for these abstractions, in terms of metaphors for system dynamics that can be captured via categoric abstractions.

Such abstractions necessarily stretch the bounds of applicable logic. Probably, asserting that ‘biology creates,’ that the results are ‘profoundly different’ and that computation and mathematics are somehow separate are imperative statements.

We do assert, however, that this is a significantly different approach to computationally friendly modeling; in concert with better known abstractions, the promise is for radical improvements in many domains.

References


Kaplan, Shai, Brez, Frédéric, Dégot, Aline, Uri, 2008. The incoherent feed-forward loop can generate non-monotonic input functions for genes. Molecular Systems Biology 4 (208), 9.


