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Second Order Isomorphism: A Reinterpretation and Its Implications in Brain and Cognitive Sciences

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Abstract

Shepard and Chipman's second order isomorphism describes how the brain may represent the relations in the world. However, a common interpretation of the theory can cause difficulties. The problem originates from the static nature of representations. In an alternative interpretation, I propose that we assign an *active* role to the internal representations and relations. It turns out that a collection of such active units can perform analogical tasks. The new interpretation is supported by the existence of neural circuits that may be implementing such a function. Within this framework, perception, cognition, and motor function can be understood under a unifying principle of analogy.

Introduction

One of the central tenets in neuroscience is that neurons receive incoming spikes, process that spatial or temporal information, and then pass on the transformed information for further analysis. Also, neurons that fire together develop strong connections (Bliss and Collingridge 1993). Thus, the neurons represent features in the input, and connections encode relational context among features. This viewpoint is analogous to the second order isomorphism by Shepard and Chipman (1970; below, just S&C). However, a problem can arise depending on how we interpret S&C's theory.

The difficulty comes from the *static* role assigned to representations. In this paper, the representations and the relations are given an active role. When working as a collection, these active units can perform an analogical function. In fact, a similar active approach has been employed in previous work, resulting in the emergence of analogical (Hofstadter 1985; Mitchell 2001) or metaphorical (Narayanan 1999) functionality.¹ An important observation advanced in this paper is that the function of active representations and relations are very similar to that of neurons, and specific circuits in the cortex and the thalamus can actually *implement* analogical functions. Analogy is commonly attributed to higher cognitive faculties only, but it does not always have to be the case (Chalmers et al. 1992); it may be part of a larger set of human brain function including perception and motor function. I will discuss in the end how such an

¹Analogy and metaphor are closely related in that they refer to similarities in relations and attributes although the relative degree in each may differ (Gentner 1989).

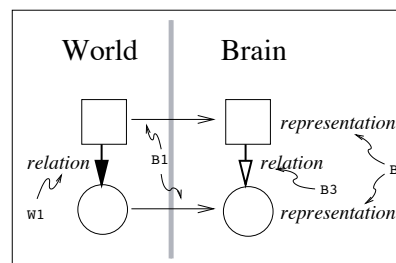


Figure 1: **S&C's Second Order Isomorphism.** There are two objects, one square and one round in the world (on the left). The internal representations in the brain of these two objects are shown on the right. The vertical arrows represent the relations between the objects. The two horizontal arrows represent mapping from the world to the brain which is initiated by sensory transduction. Note: The square and circle on the right (in the brain) are just there for the ease of reference. They can be removed without causing any change in content (this applies to the rest of the figures).

analogical framework can allow us to better understand the nature of cognition and brain function.

Common Interpretations

Under second order isomorphism the brain needs to find the relation between the (1) relations between external objects and (2) relations between internal representations (figure 1). S&C's theory seems to be more appropriate in modeling how our brain represents the world than Locke's Isomorphism (Edelman 1998, 1999). In physical terms, we can interpret the figure as follows: (1) relation in the world (W1; coincidences in sensory events) (2) arrows from world to brain (B1; sensory transduction), (3) representations in the brain (B2; afferent connections), and (4) relation in the brain (B3; lateral connections). Of these, let us focus on what is available in our brain (B1–B3). If we take for granted the information our sensory transducers tell us, we can drop B1 from our discussion and focus on just B2 and B3.

An implicit message in figure 1 is that two objects are represented, and some brain process then judges the relationship between the two (the open arrow). Making this point more explicit, we can illustrate S&C's theory as in figure 2a (the diamond box). We can see that a difficulty can arise in such an interpretation; something has to perform the comparison function, but this creates an ever increasing levels in a hierarchical way (i.e. higher areas

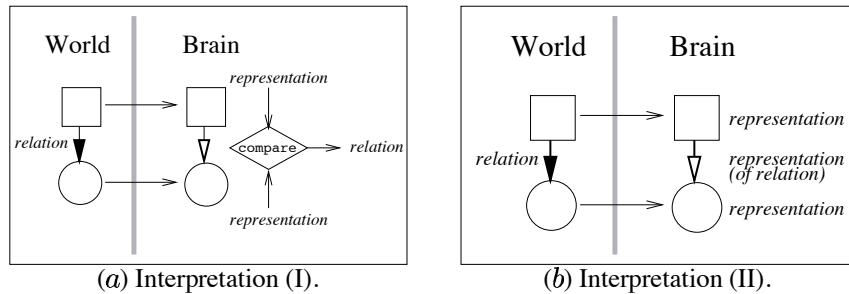


Figure 2: **Common Interpretations of Second Order Isomorphism.** (a) An explicit comparison mechanism is necessary to judge the relations between the two representations. (b) The comparison box is replaced by a representation of relation. However, this figure still requires a third-party to *evaluate* the representation of relation.

judging the output relation in the lower areas). However, as Hilgetag et al. (1996) noted, it is hard to determine a strict hierarchy among cortical maps (in this case, between visual areas). Also, as Zeki (2001) suggests, integration of these information may be a nonhierarchical process. Thus, representing something and delaying the interpretation until later may not work very well.

One can argue that the lateral connections *represent* the similarity relation, not requiring a separate interpreter (figure 2b). However, we still need something to evaluate (or interpret) the resulting representation. Thus, this reformulation just replaces the need for one kind of interpreter with another.

Assigning an Active Role to Relation

What can a relation be if it should not be a representation? The problem seem to come from representations and relations playing a *static* role. What if we assign an active role to the representations as shown in figure 3a? In the figure, I assigned an active role to the relation arrow itself, allowing one representation to invoke another. Thus the activation of the internal representation of the square *invokes* (or turns on) that of the circle, and vice versa.

Now consider how can we use this new active relation (note that it is *directional*) to describe the relations in the world. First, we have to know what kinds of relations exist in the world. There are two basic relations: spatial and temporal relations. Spatial relations are between objects, and they are causally bidirectional.² On the other hand, temporal relations are between events, and they are causally directional. When one event precedes the other, the reverse cannot happen simultaneously.

In the brain, action potentials only propagate in one direction along the axon, and the adaptation of synapses tend to learn causality (Song et al. 2000). Such connections are ideal for implementing temporal relations, but what about spatial relations? If we pair a unidirectional arrow from A to B with a reciprocal one from B to A, then we can indeed represent spatial relations with only directional arrows. If representations for object A and B simultaneously activate through mutual excitation, then

²Note that *causal* simply means that one event precedes the other in time.

they can represent the spatial relation between the two. So, let us update our figure again to include backward relational arrows (figure 3b). We can now think in terms of *temporal* relations only, because spatial relations seems to be a special case of temporal relations (at least in the brain).

The Role of Active Relations and its Neural Basis

In the previous section, I replaced the representation for relation by an active relation. What about the representations for the objects (or events)? Representation is an inherently static term (like a symbol), thus, we should take a more active viewpoint and ask *what action occurs* when a neuron detects a pattern in its incoming input, rather than focusing only on what a neuron represents. Knowing what representations *do* may be as important as knowing what they *stand for*.

To discover the relationship between things in the world, we need the motor capabilities as much as we need sensors. Thus, between the world and the brain there must be a backward arrow from the brain to the world. The resulting diagram is shown in figure 3c. This addition is crucial in learning the relations in the world (O'Regan and Noe 2001). The final diagram looks very similar to the basic circuitry in our brain. How can this final figure help us understand the mechanisms of the brain? The key is to understand what is the *action* taken by a neuron, no less than to know what it represents.

Active Relations: A Primitive for Analogical Processing

Now we have a single active functional unit: a neuron that fires a spike along the *active relational arrow* as soon as it detects a certain input feature. This unit alone cannot achieve much, neither can a serial chain of such units. The true power of this simple unit is revealed when it is used in a massively parallel way. This may be an obvious line of thought because that is what our brains seem to do. However, it turns out that the collective effort of these simple units can embody a simple yet powerful function of analogy.

We have to simplify matters to see how such neurons can process analogy. Let us assume there are six neurons in an imaginary creature's brain inhabiting the world

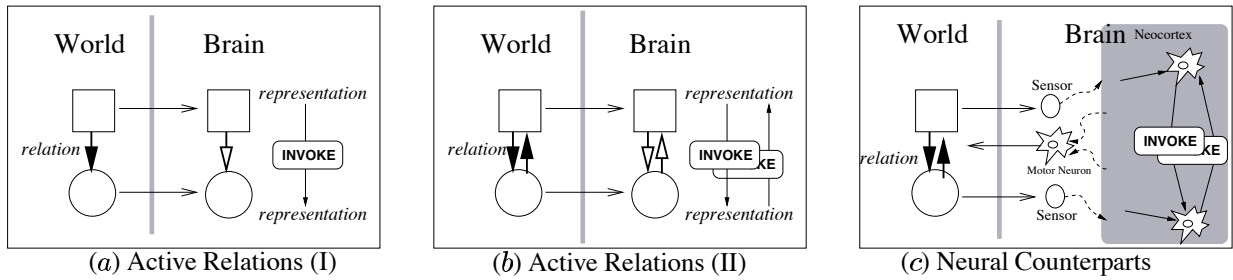


Figure 3: **A New Interpretation of Second Order Isomorphism.** (a) In this new interpretation of S&C's theory, an active role is assigned to the relation arrow. Notice that the INVOKE arrow is a single arrow, not one arrow going into and another leaving out of the box. Thus, the rounded box signifies that the arrow actually performs an *action*. (b) Backward relational arrows are added in the brain to account for the mutual, but directional nature of relations. With two relational arrows, both spatial and temporal relations can be implemented. (c) The neural counterparts of (b) are shown. The limiting term *representation* is removed, and the motor reaction (backward arrow from the brain to the world) is added. Sensory transducers are also explicitly shown.

of fruits (figure 4). After the fruit brain experiences the world of fruits, it will learn the co-occurrences between features and establish relational arrows as shown in the figure (arcs with arrows). Also suppose that the brain is partitioned into several specialized map areas (or partitions), as in cortical maps. Now suppose <apple>, <orange>, and <word-red> were presented to the creature simultaneously. If we track the activation, we can see that these detectors will turn on: apple detector, orange detector, color-red detector, color-orange detector, and finally, word-red detector. These activations are *input-driven*. Because the neurons are active, as soon as they detect what they are familiar with, they send out signals through the relational arrows horizontally across the cortex. As a result of this second order activation, the word-orange detector turns on, even without input. Now, here is the crucial moment. We can ask this question: *which neuron's firing was purely cortically-driven?* (note that we can view this as a filtering process). The result of the filtering is then <word-orange>. The significance of this observation is that this process is very similar to solving analogical problems. The input presented to the creature is basically an analogical query: <apple>:<orange> = <word-red>:<?>. The filtered cortical response <word-orange> can then be the *answer* to this query.³ Thus, active neurons can perform a rudimentary analogical function when the responses are filtered properly.

However, things can get complicated when combinations of objects are used as a query. Let us extend the creature's feature detectors to include concepts of small and big (not shown in the figure). Then we can allow the creature to learn the relations again. We can then present an analogical query like this: <big><apple>:<small><apple> = <big><orange>:<?>. In this case, if we follow the same steps as above we come across a problem. Because the answer we expect (i.e. <small> <orange>) already appeared in the query, if we look for purely

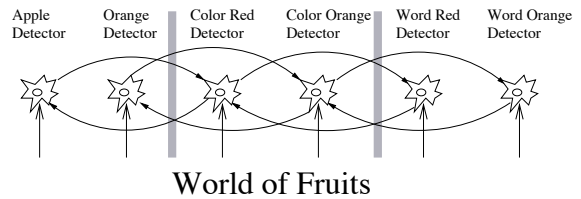


Figure 4: **World of Fruits.** A brain with object, color, and word detector neurons is shown. The six neurons each respond to these input features as labeled above. At the bottom is the fruit world, and the thick vertical arrows represent afferent input. The horizontal arcs are the relational arrows that point to their most frequently co-occurring counterparts that have been learned through experience. The gray vertical bars represent the partitioning of the brain into separate map areas (from the left to right, object map, color map, and word map). Note that for simplicity, the word-orange detector connects only to the color-orange detector, but not the orange detector, i.e. it is a word-color-orange detector, not a word-object-orange detector.

cortically-driven activations, the answer will be <word-red> <word-orange>. However, we can overcome this problem if we ask: *what are the most cortically-driven activities in each partition of the brain?* Because <big> and <apple> appeared in the input twice but <small> and <orange> appeared only once, the latter two can be selected, as well as the purely cortically driven activities listed above. Thus, even for derived activities that are input-driven, those that are less input-driven can survive and the correct analogical response can still be found among such activities that are more cortically-driven within each partition (or area). Note that <color-orange> also survives the filtering, but what is more important here is that a simple filtering process as described above can generate a *small subset of potential answers* to analogical queries. Although the simple analogical query presented above has a straight forward answer, in more complex analogical problems, there can be multiple answers depending on the interpretation (Hofstadter and Mitchell 1994; Mitchell 2001).

In this section, I have shown that active neurons that detect input features and establish relational contexts can collectively perform a rudimentary analogical function.⁴

³There is an issue of how the presence of <word-red> can affect the outcome at all. This problem will be discussed later in the discussion section.

⁴Analogical tasks can become much more complex than the ones shown here. The example in this paper is decidedly simple

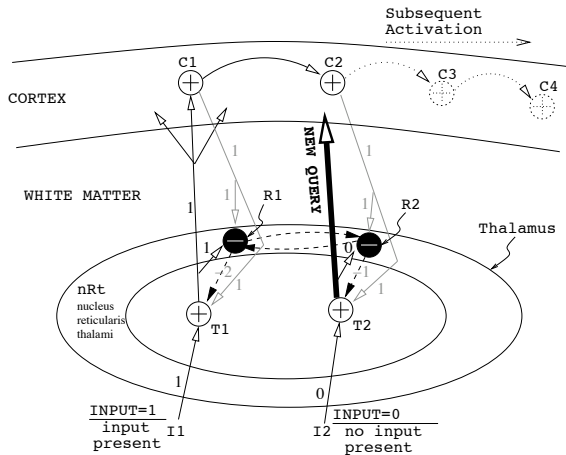


Figure 5: Analogical Filtering in the Thalamus. The diagram shows a simplified thalamo-cortical loop that can perform analogical completion and selection and then propagate the selection back to the cortex. All connections shown are based on known anatomy of the thalamus and the cortex (Mumford 1995). I1 and I2 are input fibers, T1 and T2 are thalamic relay cells, and R1 and R2 are inhibitory nRt cells. C1, C2, C3, and C4 are cortical neurons (each is a set of neurons ranging multiple layers in a single cortical column). The neurons are either excitatory (+) or inhibitory (-), and the arrows are axons (pointing in the direction of action potential propagation). The numbered labels on each arc show the activity being carried. Black solid arrows are ascending fibers to the cortex and the cortico-cortical connections (relational arrows), and gray solid arrows are cortico-thalamic feedback. Black dashed arrows are inhibitory connections. The diagram shows a scenario when an input was presented to C1, which excites C2, and in turn generates the feedback from C2 to T2, which is then retransmitted to the cortex as a new query (ascending thick black arrow). The selection decision for further propagation to the cortex depends on the relative excitation and inhibition T1(T2) receive from C1(C2) and R1(R2). On the right of C2 (dotted) in the cortex is the subsequent cascade of analogical completions. Note that to avoid clutter, reciprocal connections in the cortex are not shown.

But does the brain function in such a way? In fact, an exact circuit that may be implementing such a function exists in the brain.

Neural Basis of Analogical Completion and Filtering

Two basic mechanisms are needed to account for the proposed analogical function: completion and filtering. Below, I will discuss how the cortico-cortical connections and the thalamo-cortical loop can implement these two mechanisms.

Completions may be accomplished by the long-range cortico-cortical connections (Mumford 1992). As mentioned earlier, synapses are strengthened when the presynaptic activity precede postsynaptic activity (Song et al. 2000), thus the connections can implement causal relations. Also, specific patterns of connections observed in animals (e.g. visual cortex of monkeys; Blasdel 1992) show how such patterns can implement specific completion functions. Computational models also showed

to clearly illustrate the basic mechanism.

how such patterns can encode feature co-occurrence and how they can dictate the performance of the model (Choe 2001; Geisler et al. 2001).

For filtering, a separate mechanism is necessary. In the thalamo-cortical loop, there exists a massive feedback from the cortex to the thalamus and an inhibition mechanism within the nucleus reticularis thalami (nRt) on the surface of the thalamus (Mumford 1995). This particular architecture has been thought to be involved in the analysis and synthesis of new memories (MacKay 1956), active blackboard (Harth et al. 1987; Mumford 1995), global workspace (Newman et al. 1997), and finally, generating attention and consciousness (Crick and Koch 1990). It turns out that these feedforward and feedback connections from nRt to the cortex together with the nRt inhibitions can filter the feedback from the cortex to promote the most cortically-driven feedback, i.e. the analogical answers. Let us first see how the purely cortically-driven activities are selected (figure 5). In the thalamus, ascending fibers (T1 to C1) branch out and excite the inhibitory nRt neuron R1 (T1 to R1). When the feedback from C1 to T1 comes back, it branches and stimulates R1. As a result, if the descending feedback had a matching ascending signal, the inhibition T1 receives is twice as high as other neurons in the thalamus that are activated by purely cortically-driven feedback (i.e. that of T2). If the synaptic weights are appropriate (i.e. $w_{TC} = 2$ and $w_{TR} = 1$)⁵, at T1 the feedback will cancel out, but at T2 the feedback will survive the inhibition and be retransmitted to the cortex (the *new query* arrow). Such a surviving cortical feedback, together with the input stimulus at the next moment form a new analogical query to the cortex, and the same process is repeated. That is, C2 elicits activities in C3, and in turn C4 through the thalamo-cortical loop (note that they can be quite far away). For the selection of the *most cortically driven* feedback, the mutual inhibitions in the nRt layer (e.g. between R1 and R2) may disinhibit (inhibiting an inhibitory neuron results in less net inhibition at the target; figure 5) each other and allow the more cortically driven feedback to go back to the cortex, even when all current cortical activities are input driven.

Discussion

The neural mechanisms described in this paper can only account for simple kinds of analogies, and in some case it can even seem as simple pattern completion. For example, $\langle \text{orange} \rangle = ?$ will result in the same answer $\langle \text{word-orange} \rangle$ as in the *Active Relations:...* section. How can the term $\langle \text{word-red} \rangle$ in the original query affect the outcome at all? For this, I believe that among many possible completions, the general map area (i.e. the partitions in figure 4) that are activated by input gets higher preference. In this example, the fruit-map, word-map and color-map will turn on, thus purely cortical activations in other general maps (say odor-map, etc.) will not be as salient as that of $\langle \text{word-orange} \rangle$. Thus, in this

⁵Here, w_{YX} is the synaptic connection strength from neuron X to neuron Y.

way, the presence of <word-red> can indeed affect the outcome of the analogical query. A more precise neural mechanism for this kind of selection among areas (or maps) needs to be investigated further.

Researchers regard the analogical capability as the crux of high-level cognition (see Gentner et al. 2001 for a collection of current work on analogy). However, analogy does not need to be limited to high-level cognition. Recent results suggest that analogy may be needed in perception as well (Morrison 1998), and such an ability emerging in perceptual systems may even be a crucial *requirement* for cognitive development (Chalmers et al. 1992). Then it is not unthinkable that motor function also employ analogy in a similar manner (cf. sensory motor contingency theory by O'Regan and Noe 2001), thus we can then start to understand perception, cognition, and motor function under the unifying framework of analogy.

How can such a diverse functionality be integrated under a single framework of analogical processing? Massive connections exist within and across different functional areas in the brain, and the sensory/motor maps are topologically organized, i.e. nearby neurons are responsive to nearby features in the sensory space (Kohonen 1982; von der Malsburg 1973). Within each map, the feature detectors and the cortico-cortical connections learn to encode the relations (Choe 2001). It is possible that cognitive maps also have a topological organization where nearby areas learn to encode similar concepts, such as semantic maps or episodic memory maps (Miikkulainen 1993). When the sensory, cognitive, and motor maps are connected in an orderly way preserving their local topology, analogies can be drawn within and (more importantly) *across* different functional domains.

Within this huge number of maps specializing in different tasks, a cascade of multiple analogical completions can be going on in parallel, synchronized at each moment by the 40Hz rhythm to hold an instantaneously coherent state (Gray 1999; Mumford 1995). Such a state can then pose as another analogical query, and the process can repeat. When the cascade reaches a motor area, behavior will be generated. Memory content may also enter the analogical cascade, and this quasi-static contribution can prevent the continuously changing input stream from causing random cascades, thereby maintaining a more goal-directed and stable behavior. Specific mechanisms of how the memory content enters the thalamo-cortical loop, and how analogies are archived in long-term memory should be studied further.

Neuroscience research has revealed a lot about perception and motor abilities in the brain, but understanding the cognitive faculty still remains elusive. Investigation into cognitive functions can proceed under the analogical framework, where we can infer the functionality of the higher areas by backtracking the connections to the perceptual and motor areas and study their topology and analogical links. Specific predictions regarding the layout of the higher centers may be made based on the topology of the lower centers and the connection structure between the two, and experiments can then focus on verify-

ing these predictions. For example, there are orientation maps with smoothly changing orientation preference in V1 (primary visual cortex; Blasdel 1992), and there are object maps in TE (temporal area E; Tanaka 1996) that also change smoothly (for example, rotation of a head). The analogical framework predicts that there will be an orderly mapping from V1 to TE that preserve such local topology across different representation spaces.⁶ Similar mappings may exist between sensory and cognitive areas, and if such a mapping is found, we can start to understand the abstract cognitive functions based on concrete perceptual architecture.

The strong connection made in this paper between analogical function and specific neural circuitry can help us better understand both. The functionality of the target area of a neuron can be studied to understand *what action occurs* when a neuron detects a certain feature in the input. Such a study can reveal the kinds of relations implemented in the brain, thus providing us with insights into what kinds of analogies are possible. The mechanisms of neural circuits can also be further revealed by carefully designed analogical tests in perception, cognition, and motor function, and also in a combination of these different domains. Different types of unimodal and cross-modal analogical tasks can reveal how the different cortical areas are related and how they invoke each other. In studying such mappings across tasks and modalities, understanding the co-occurrence statistics of natural signals becomes increasingly important as they may give us a hint on how the connections are organized in the brain (Choe 2001; Simoncelli and Olshausen 2001).

Conclusion

In this paper, I analysed the difficulties that the common interpretations of S&C's second order isomorphism can cause in understanding the brain. I proposed an *active* role for representations and relations, and it turned out that collectively they can perform an *analogical function*. An important connection between analogical function and a specific brain circuit was then established, providing support for the new interpretation. This new viewpoint allows us to understand perception, cognition, and motor function under a unifying framework of analogy, and it can help us take a more focused approach in brain and cognitive sciences.

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⁶Although the pathway from V1 to TE is not direct, involving V2, V4, and TEO areas, but successive mappings within this path can reveal how V1 and TE are topologically mapped. Also, see Edelman (1995) for more on smooth representation spaces for complex visual objects.

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