Laws and Makeups in Context-Dependent Reduction Relations

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Abstract

One of the problems encountered in Philosophy of Mind is that cognitive theories have a nontrivial dependence on the context of specific neurological makeups or mechanisms of individuals and species. Due to this context-dependency, for example, regularities or relationships between cognitive states are not considered genuine laws and cannot be directly related to neurological laws. The classical approaches to reduction such as bridge law reduction, functional reduction and interpretation mappings do not explicitly address this context-dependency. In this paper it is shown how these reduction approaches can be refined to incorporate the context-dependency. It is shown how the context-dependent reduction approaches obtained make explicit in which sense laws or regularities in a cognitive theory on the one hand relate to neurological laws and on the other hand to specific makeups.

Introduction

The status of cognitive science or psychology[1] has since long been the subject of debate within the philosophical literature; e.g. (Bennett and Hacker, 2003; Bickle, 1992, 1998, 2003; Churchland, 1986; Churchland, 1989; Kim, 1996, 1998, 2005). Among the issues questioned are the existence and status of cognitive laws, and the connection of cognitive concepts and laws to reality. For example, it is claimed that cognitive science is not an independent science; cognitive laws as genuine laws do not exist; cognitive concepts have no principled, unambiguous relation to reality; and cognitive explanations are not genuine causal explanations; see, for example, (Bennett and Hacker, 2003, pp. 361-372; Bickle, 1998, pp. 103-164; Kim, 1996, pp. 216-221). These claims imply that cognitive science is at least not a science comparable to general sciences such as physics and chemistry. Similar conclusions are sometimes drawn about other so-called special sciences such as biology and social sciences. Within the philosophical literature on reduction for a long time much effort has been invested to address these criticisms; e.g., (Nagel, 1961; Kim, 1996, 1998, 2005; Bickle, 1998, 2003). As the achieved results still are subject of debate, alternatives have been proposed.

In recent years much attention has been paid to explore the possibilities of the notion of *mechanism* within philosophy of science, often in relation to biology, cognitive science and neuroscience; e.g., (Craver, 2001, 2007; Craver and Bechtel, 2007; Glennan, 1996, 2008; Bechtel, 2005ab, 2007, 2008).

According to Glennan (1996), 'a mechanism underlying a behavior is a complex system which produces that behavior by the interaction of a number of parts according to direct causal laws'. In (Bechtel, 2005), the concept is defined as follows: 'A mechanism is a structure performing a function in virtue of its components parts, component operations, and their organization. The orchestrated functioning of the mechanism is responsible for one or more phenomena.'

Among the claims made is that mechanisms may provide fruitful answers to the types of debates mentioned above, and more specifically concerning explanation, reduction, situatedness, and integration of sciences. One of the issues addressed by mechanisms is how a certain (higher-level) capability is realised by organised (lower-level) operations. Usually it is proposed to leave the old-fashioned solutions that were earlier proposed (and seriously criticised) in the literature on reduction behind, and fully commit to an alternative approach based on mechanisms. For example, it is proposed to replace explanations referring to laws by explanations referring to mechanisms.

In this paper it is investigated whether the choice options really are that exclusive. More specifically, it is explored in how far certain aspects addressed by mechanisms can also be addressed by (refinements of) approaches to reduction, such as the bridge law approach (Nagel, 1961), the functional approach (Kim, 1996, 1998, 2005), and the interpretation mapping approach (Tarski, Mostowski, and Robinson, 1953). To achieve this, as a refinement context-dependent variants of these reduction approaches will be defined addressing the problematic aspects as mentioned.

The paper is organised as follows. In the next section the challenge addressed in this paper is discussed in more detail and illustrated for a simplified case study in conditioning. Subsequently three approaches to context-dependent reduction are introduced in some detail (refining bridge law reduction, functional reduction, and reduction by interpretation mappings). The next section shows how the approaches can be applied to the case study. Finally the results are discussed.

On Context-Dependency

In this section the challenge addressed is discussed in more detail and illustrated for a simplified case study concerning conditioning processes in the sea hare *Aplysia*. Using this case some of the central claims from the literature in Philosophy of Mind are illustrated:

(a) Cognitive laws are not genuine laws but depend on circumstances, for example, an organism's makeup.
(b) Cognitive laws can not be related (in a truth-preserving manner) to neurological laws

[1] In this paper, as in much literature in Philosophy of Mind, the terms 'cognitive' and 'psychological' will be used for the same.

(c) Cognitive concepts and laws cannot be related to reality in a principled manner, but, if at all, in different manners, depending on circumstances.
(d) Cognitive explanations are not genuine causal explanations.

These claims are often used as arguments against the classical approaches to reduction, as these approaches would aim to provide support for the opposite statements; e.g., (Bennett and Hacker, 2003, pp. 361-372; Bickle, 1998, pp. 103-164; Kim, 1996, pp. 216-221). A central issue here is the observation that the relationship between cognitive conceptualisation and reality has a dependency on the context of the neural makeup of individuals and species, and this dependency remains unaddressed and hidden in the classical reduction approaches. Perhaps one of the success factors of the approaches based on mechanisms is that referring to a mechanism can be viewed as a way to make this context-dependency explicit. This aspect of context-dependency, and how it can be added to the classical reduction approaches is the main focus of the current paper. To get more insight in the issue, a case study on conditioning behaviour of *Aplysia* is used.

For *Aplysia* underlying neural mechanisms of learning are relatively well understood, based on long term changes in the synapses between neurons; see, for example, (Gleitman, 2004, pp. 70-76, pp. 154-156; Hawkins and Kandel, 1984). *Aplysia* is able to learn based on the (co)occurrence of certain stimuli; for example; see (Gleitman, 2004, pp. 154-156). The behaviour before a learning phase is as follows: (1) a tail shock leads to a response (contraction), but (2) a light touch on its siphon[2] is insufficient to trigger such a response. Suppose a training period with the following protocol is undertaken: in each trial the subject is touched lightly on its siphon and then immediately shocked on its tail; as a consequence it responds by a contraction. After a number of trials (for the sake of simplicity limited to two in the current example) the behaviour has changed: the animal also responds (contracts) to a siphon touch. To describe the conditioning process by a simple cognitive theory *CT*, an internal sensitivity state for stimulus-action pairs *s-a* is assumed that can have levels low, medium and high, where high sensitivity entails that stimulus *s* results in action *a*, and lower sensitivities do not entail this response:

Cognitive theory *CT*

If s-a sensitivity is high and stimulus s occurs,
then action a occurs
If stimulus s1 and stimulus s2 occur and s1-a sensitivity is high,
and s2-a sensitivity is not high,
then s2-a sensitivity becomes one level higher

As a next step, it is considered how the mechanism behind this simple cognitive theory works at the neurological level for *Aplysia*. Roughly spoken the internal neural mechanism for *Aplysia*'s conditioning can be depicted as in Figure 1, following (Gleitman, 2004, pp. 154-156). A tail shock activates a sensory neuron SN1. Activation of this neuron SN1 activates the motoneuron MN via the synapse S1 between the two neurons; activation of MN makes the sea hare move. A siphon touch activates the sensory neuron SN2. Activation of this sensory neuron SN2 normally does not have sufficient impact on MN to activate MN, as the synapse S2 between SN2 and MN is not strong enough. After learning, the synapse S2 has become stronger and therefore activation of SN2 has sufficient impact to activate MN. If SN2 and MN are activated (almost) simultaneously, this increases the strength of the synapse S2 between them: the effect is that in this synapse more neurotransmitter is produced whenever SN2 is activated. After a number of times this leads to the situation that synapse S2 is strong enough so that activation of SN2 leads to activation of MN.

This description is on the one hand based on the specific makeup *AS* of *Aplysia*'s neural system, but on the other hand on general neurological laws. The (simple) neurological theory *NT* considered consists of the following general laws:

Neurological theory *NT*

Activations of neurons propagate through connections via synapses with high strength.
Simultaneous activation of two connected neurons increases the strength of the synapse connecting them.
When an external stimulus occurs that is connected to a neuron, then this neuron will be activated.
When a neuron is activated that is connected to an external action, then this action will occur.

The specific neural makeup *AS* of *Aplysia* is as follows:

Neural makeup *AS*

stimulus s1 connects to neuron SN1
stimulus s2 connects to neuron SN2
neuron SN1 connects to neuron MN via synapse S1
neuron SN2 connects to neuron MN via synapse S2
neuron MN connects to action a
synapse S1 has initial strength high
synapse S2 has initial strength low

How the context makes the difference

Claims (a) and (b) discussed above are illustrated by the *Aplysia* case as follows. The neurological laws in theory *NT* are general laws, independent of any specific makeup; they are (assumed to be) valid for any neural system. In contrast, the validity of the two cognitive laws in theory *CT* not only depends on these neurological laws but also on the makeup of the specific type of neural system; for example, if some of the connections of *Aplysia*'s neural system are absent (or wired differently), then the cognitive laws will not be satisfied for this organism. This shows that the cognitive laws depend on the context *AS* given by the neural makeup of *Aplysia*.

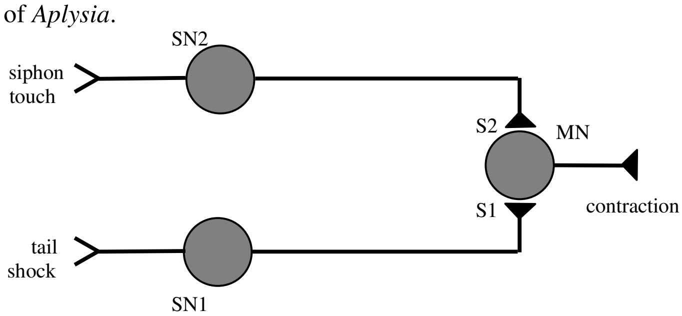

Figure 1: Makeup *AS*: neural mechanism in *Aplysia*

[2] This is a tube-shaped organ on its back.

As the neurological laws do not depend on this makeup, the cognitive laws can not be related (in a truth-preserving manner) to the neurological laws. Claim (c) can be illustrated by considering other species than *Aplysia*, with different neural makeup, but showing similar conditioning. Claim (d) is also supported by these observations, as it is difficult to consider causal relationships between chameleon-like cognitive concepts that, depending on the context, show up in reality in different forms, where virtually any physical concept can become a realisation of such a cognitive concept, as soon as an appropriate context is created around it. A central issue shown in this illustration of the four claims is the notion of makeup, which provides a specific context of neurological realisation of the cognitive concepts and laws. Indeed, the classical approaches to reduction do not include any reference to this context aspect, whereas the approaches based on the notion of mechanism explicitly refer to it. The challenge addressed below is to define variants of the classical reduction approaches that also explicitly take into account this aspect of context-dependency, and thus provide support for the claims (a) to (d) instead of ignoring them.

Context-Dependent Reduction Approaches

Reduction addresses relationships between descriptions of two different levels, usually indicated by a higher-level theory T_2 (e.g., a cognitive theory) and a lower-level or base theory T_1 (e.g., a neurological theory).[3] A specific reduction approach provides a particular *reduction relation*: a way in which each higher-level property or law a (an expression in T_2) can be related to a lower-level property or law b (an expression in T_1); this b is often called a *realiser* for a. Reduction approaches differ in how these relations are defined. Within the traditional philosophical literature on reduction, such as (Nagel, 1961; Kim, 1996, 1998, 2005), three approaches play a central role.

In the approach described by Nagel (1961) reduction relations are based on (biconditional) bridge principles $a \leftrightarrow b$ that relate the expressions a in the language of a higher-level theory T_2 to expressions b in the language of the lower-level or base theory T_1. In contrast to Nagel's *bridge law reduction*[4], *functional reduction* (e.g., Kim, 2005, pp. 98-102) is based on functionalisation of a property a in T_2 in terms of its causal task C, and relating it to a property b in T_1 performing this causal task C. From the logical perspective the notion of a *(relative) interpretation mapping*[5] is often used to formalise reduction relations (e.g., Tarski, Mostowski, and Robinson, 1953; Kreisel, 1955; Schoenfield, 1967, pp. 61-65; Hodges, 1993, pp. 201-263). These approaches relate the two theories T_2 and T_1 based on a mapping φ relating the expressions a of T_2 to expressions b of T_1, by defining $b = \varphi(a)$. Within philosophical literature, Bickle (1992) discusses an interpretation approach with roots in (Hooker, 1981; Churchland, 1986, 1989).

A general setting for context-dependent reduction

For each of the three approaches to reduction as mentioned, a context-dependent variant will be defined. As a source of inspiration (Kim, 1996, pp. 233-236) is used, where it is briefly sketched what he calls a local or structure-restricted form of bridge law reduction based on bridge laws of the form $S \rightarrow (a \leftrightarrow b)$, where S denotes the organisms makeup. In this section it is shown how this idea can be worked out for each of three approaches, obtaining variants making the dependency on a specific makeup explicit.

In context-dependent reduction the aim is to identify a set of contexts and to relate the different sets of realisers to these contexts. When contexts are defined in a sufficiently fine-grained manner, within one context the set of realisers can be taken to be unique. The contexts can (but do not need to) be chosen in such a manner that all situations in which a specific type of realisation occurs are grouped together and described by this context. For example, in cognitive science such a grouping could be based on species, i.e., groups of organisms with (more or less) the same architecture.

In a first approach to context-dependent reduction, a context can be taken to be a description S (of an organism or system with a certain structure) by a set of statements within the language of the lower-level theory T_1. For a given context S as a parameter, for each expression of the higher-level theory T_2 there exists a realiser within the language of T_1. Context-dependent reduction as sketched by Kim (1996, pp. 233-236), indeed assumes that the contexts all are specified within the same base theory T_1. However, if mental properties (for example, having certain sensory representations) are assumed that can be shared between, for example, biological organisms and robot-like architectures, it may be useful to allow contexts that are described within different base theories. In the context-dependent reduction approaches developed below, a collection of lower-level theories $\mathcal{T}_1$ is assumed and for each theory T in $\mathcal{T}_1$ a set of contexts $\mathcal{C}_T$, such that each organism or system is decribed by a specific theory T in $\mathcal{T}_1$ together with a specific context[6] or makeup S in $\mathcal{C}_T$; these contexts S are assumed to be descriptions in the language of T and consistent with T. For the case that within one context only one realisation is possible, the theories T in $\mathcal{T}_1$ and contexts S in $\mathcal{C}_T$ can be used to parameterise the different sets of realisers that are possible. Below it is shown how contexts can be incorporated in the three reduction approaches discussed above.[7]

[3] Note that this can be extended to multiple levels; for example, reduction relations may be defined between a neurological theory and biochemistry as well.

[4] As in the literature bridge principles are often called bridge laws, although they often are claimed not to be laws, the latter term will be used.

[5] Sometimes called *translation*.

[6] Note that the context is in fact the pair (T, S), but often just S is called the context, assuming that it is clear that (T, S) is meant.

[7] When the collection of theories $\mathcal{T}_1$ is taken a singleton $\{T_1\}$ consisting of one theory T_1 and the set of contexts $\mathcal{C}_{T_1}$ is taken a

Context-dependent bridge law reduction

For this approach, a unique set of realisers is assumed within each context S for a theory T in $\mathcal{T}_1$; this is expressed by context-dependent biconditional bridge laws. Such context-dependent bridge laws are parameterised by the theory T in $\mathcal{T}_1$ and context S in $\mathcal{C}_T$, and can be specified by

$$a_1 \leftrightarrow b_{1,T,S}, \ldots, a_k \leftrightarrow b_{k,T,S}$$

Given such a parameterised specification, the criterion of context-dependent bridge law reduction for a law $L(a_1, \ldots, a_k)$ of T_2 is formulated (in two equivalent manners[8]) by[9]:

(i) $T_2 \vdash L(a_1, \ldots, a_k) \quad \Rightarrow$
$\forall T \in \mathcal{T}_1 \; \forall S \in \mathcal{C}_T$
$T \cup S \cup \{a_1 \leftrightarrow b_{1,T,S}, \ldots, a_k \leftrightarrow b_{k,T,S}\} \vdash L(a_1, \ldots, a_k)$

(ii) $T_2 \vdash L(a_1, \ldots, a_k) \quad \Rightarrow$
$\forall T \in \mathcal{T}_1 \; \forall S \in \mathcal{C}_T \quad T \cup S \vdash L(b_{1,T,S}, \ldots, b_{k,T,S})$

Here $T \vdash A$ denotes that A is derivable from T. Note that this notion of context-dependent bridge law reduction implies unique realisers (up to equivalence) per context: when $b_{T,S}$ and $b'_{T,S}$ are known to be non-equivalent in T, then from $a \leftrightarrow b_{T,S}$ and $a \leftrightarrow b'_{T,S}$ the contradiction $b_{T,S} \leftrightarrow b'_{T,S}$ would follow. So to obtain context-dependent bridge law reduction in cases of multiple realisation, the contexts are defined with such a fine grain-size that within one context unique realisers exist.

Context-dependent functional reduction

For a given collection of context theories $\mathcal{T}_1$ and sets of contexts $\mathcal{C}_T$, for context-dependent functional reduction a first step is that a joint causal role specification $C(P_1, \ldots, P_k)$ is identified such that it covers all relevant properties of theory T_2. As an example, consider the case discussed in (Kim, 1996, pp. 105-107). Here the joint causal role specification *C(alert, pain, distress)* for three related mental properties is described by:

If x suffers tissue damage and is normally alert, x is in pain
If x is awake, x tends to be normally alert
If x is in pain, x winces and groans and goes into a state of distress
If x is not normally alert or is in distress, x tends to make typing errors

By a process of Ramseification[10] the following joint causal role specification is obtained. There exist properties P_1, P_2, P_3 such that $C(P_1, P_2, P_3)$ holds, where $C(P_1, P_2, P_3)$ is

If x suffers tissue damage and has P1, x has P_2
If x is awake, x has P_1
If x has P_2*, x winces and groans and has* P_3
If x has not P_1 *or has* P_3*, x tends to make typing errors*

singleton $\{S\}$ consisting of the empty specification $S = \phi$, then the general (non-context-dependent) reduction approach is obtained.

[8] The equivalence follows from the fact that adding the bridge laws creates a definitional extension, and a definitional extension of a theory is a conservative extension; see, e.g., (Schoenfield, 1967, p. 41, 57-61; Hodges, 1993, pp. 59-60, 66).

[9] Note that in the notation $L(a_1, \ldots, a_k)$ the arguments refer to properties as subformulae; the notation expresses how a proposition is built up out of these properties.

[10] Following (Ramsey, 1929) and (Lewis, 1972); see also (Kim, 1996, pp. 105-107)

The property '*being in pain'* of an organism is formulated in a functional manner as follows:

There exist properties P_1, P_2, P_3 *such that* $C(P_1, P_2, P_3)$ *holds and the organism has property* P_2.

Similarly, '*being alert*' is formulated as:

There exist properties P_1, P_2, P_3 *such that* $C(P_1, P_2, P_3)$ *holds and the organism has property* P_1.

A first criterion for context-dependent functional reduction is that for each theory T in $\mathcal{T}_1$ and context S in $\mathcal{C}_T$ at least one instantiation of the joint causal role specification within T exists:

$$\forall T \in \mathcal{T}_1 \; \forall S \in \mathcal{C}_T \; \exists P_1, \ldots, P_k \quad T \cup S \vdash C(P_1, \ldots, P_k)$$

The second criterion for context-dependent functional reduction, concerning laws or regularities L is

$T_2 \vdash L(a_1, \ldots, a_k) \quad \Rightarrow$
$\forall T \in \mathcal{T}_1 \; \forall S \in \mathcal{C}_T \; \forall P_1, \ldots, P_k \; [\, T \cup S \vdash C(P_1, \ldots, P_k) \Rightarrow$
$T \cup S \vdash L(P_1, \ldots, P_k) \,]$

In general this notion of context-dependent functional reduction may still allow multiple realisation within one theory and context. However, by choosing contexts with an appropriate grain-size it can be achieved that within one given theory and context unique realisation occurs. This can be done by imposing the following additional criterion expressing that for each T in $\mathcal{T}_1$ and context S in $\mathcal{C}_T$ there exists a unique set of instantiations (parameterised by T and S) realising the joint causal role specification $C(P_1, \ldots, P_k)$:

$\forall T \in \mathcal{T}_1 \; \forall S \in \mathcal{C}_T \;\; \exists P_1, \ldots, P_k \; [\, T \cup S \vdash C(P_1, \ldots, P_k) \;\&$
$\forall Q_1, \ldots, Q_k \; [\, T \cup S \vdash C(Q_1, \ldots, Q_k) \Rightarrow$
$T \cup S \vdash P_1 \leftrightarrow Q_1 \;\&\; \ldots \;\&\; P_k \leftrightarrow Q_k \,]\,]$

This *unique realisation criterion* (also called *strictness criterion*) guarantees that for all systems with theory T and context S any basic property in T_2 has a unique realiser, parameterised by theory T in $\mathcal{T}_1$ and context S in $\mathcal{C}_T$. When also this third criterion is satisfied, a form of reduction is obtained that we call *strict context-dependent functional reduction*. Based on the unique realisation criterion, the universally quantified form for relations between laws is equivalent to the following existentially quantified (over P_1, …, P_k) variant:

$T_2 \vdash L(a_1, \ldots, a_k) \quad \Rightarrow$
$\forall T \in \mathcal{T}_1 \; \forall S \in \mathcal{C}_T \; \exists P_1, \ldots, P_k \; [T \cup S \vdash C(P_1, \ldots, P_k) \;\&$
$T \cup S \vdash L(P_1, \ldots, P_k) \,]$

Context-dependent interpretation mappings

To obtain a form of context-dependent interpretation, the notion of interpretation mapping can be generalised to a multi-mapping, parameterised by contexts. A *context-dependent interpretation* of a theory T_2 in a collection of theories $\mathcal{T}_1$ with sets of contexts $\mathcal{C}_T$ specifies for each T in $\mathcal{T}_1$ and context S in $\mathcal{C}_T$ an appropriate mapping $\varphi_{T,S}$ from the expressions of T_2 to expressions of T: a multi-mapping

$$\varphi_{T,S} \; (T \in \mathcal{T}_1, S \in \mathcal{C}_T)$$

from theory T_2 to theories T in $\mathcal{T}_1$ parameterised by theories T in $\mathcal{T}_1$ and contexts S in $\mathcal{C}_T$. Such a multi-mapping is a context-dependent interpretation mapping when it satisfies the property that if a law (or regularity) L can be derived from T_2, then for each T in $\mathcal{T}_1$ and context S in $\mathcal{C}_T$ the corresponding $\varphi_{T,S}(L)$ can be derived from $T \cup S$:

$$T_2 \vdash L \Rightarrow \forall T \in \mathcal{T}_1 \ \forall S \in \mathcal{C}_T \ \ T \cup S \vdash \varphi_{T,S}(L)$$

An assumption usually made, is that the mappings are compositional with respect to logical connectives:

$$\varphi_{T,S}(A_1 \wedge A_2) \ = \ \varphi_{T,S}(A_1) \wedge \varphi_{T,S}(A_2)$$
$$\varphi_{T,S}(A_1 \vee A_2) \ = \ \varphi_{T,S}(A_1) \vee \varphi_{T,S}(A_2)$$
$$\varphi_{T,S}(A_1 \rightarrow A_2) \ = \ \varphi_{T,S}(A_1) \rightarrow \varphi_{T,S}(A_2)$$
$$\varphi_{T,S}(\neg A) \ = \ \neg \varphi_{T,S}(A)$$
$$\varphi_{T,S}(\forall x\, A) \ = \ \forall x \ \varphi_{T,S}(A) \qquad \varphi_{T,S}(\exists x\, A) \ = \ \exists x \ \varphi_{T,S}(A)$$

Note that also here within one theory T in $\mathcal{T}_1$ and context S in $\mathcal{C}_T$ multiple realisation is still possible, expressed as the existence of two essentially different interpretation mappings $\varphi_{T,S}$ and $\varphi'_{T,S}$, i.e., such that it does not always hold that $\varphi_{T,S}(a) \leftrightarrow \varphi'_{T,S}(a)$. An additional criterion to obtain unique realisation per context (*strictness criterion*) is: when for a given theory T in $\mathcal{T}_1$ and context S in $\mathcal{C}_T$ two interpretation mappings $\varphi_{T,S}$ and $\varphi'_{T,S}$ are given, then for all a it holds that $T \cup S \vdash \varphi_{T,S}(a) \leftrightarrow \varphi'_{T,S}(a)$. When for each theory and context this additional criterion is satisfied, the interpretation is called a *strict interpretation*.

A Context-Dependent Reduction Case

In this section the context-dependent approaches introduced above are illustrated for the simplified case study on conditioning processes in *Aplysia* introduced before. The cognitive theory is specified more formally as follows.

Cognitive theory *CT*

sensitivity(s, a, high) & observesstimulus(s) → performsaction(a)
observesstimulus(s1) & observesstimulus(s2) &
sensitivity(s1, a, high) & sensitivity(s2, a, v) and v<high →
sensitivity(s2, a, s(v))

Here *s(v)* is a short notation for the level next to[11] *v*. In more formal terms the example neurological theory *NT* used consists of the following general laws:

Neurological theory *NT*

connectedvia(X, Y, S) & activated(X) & synapsestrength(S)> B → activated(Y)
connectedvia(X, Y, S) & synapsestrength(S) = v & activated(X) & activated(Y) → synapsestrength(S, d(v))
stimulusconnection(X, Y) & occurs(X) → activated(Y)
actionconnection(X, Y) & activated(X) → occurs(Y)

Here *B* is the threshold for activation of *Y*, and *d(v)* is a function that determines the increased value[12] for *v*. *Aplysia*'s makeup *AS* as described above can be specified more formally as follows:

Neural makeup *AS*

stimulusconnection(s1, SN1)	*stimulusconnection(s2, SN2)*
connectedvia(SN1, MN, S1)	*connectedvia(SN2, MN, S2)*
synapsestrength(S1) = v1	*synapsestrength(S2) = v2*
actionconnection(MN, a)	

[11] More specifically: *s(low) = medium*, and *s(medium) = high*

[12] For the sake of simplicity it is assumed that values below *B'* are mapped to values between *B'* and *B* and the latter values are mapped to values above *B*.

Here *v1* and *v2* are initial values for the synapses *S1* and *S2* with *v1>B* and *v2<B'*. An interpretation mapping from the cognitive theory *CT* to the neural theory *NT* and context *AS* can be defined as follows. Suppose within context *AS*, stimulus *s* is indirectly connected to the motoneuron *MN* via synapse *S*, then:

$\varphi_{NT,AS}$*(sensitivity(s, a, low)) = synapsestrength(S) < B'*
$\varphi_{NT,AS}$*(sensitivity(s, a, medium)) = B' ≤ synapsestrength(S) ≤ B*
$\varphi_{NT,AS}$*(sensitivity(s, a, high)) = synapsestrength(S) > B*

Note that this reduction relation depends on the context *AS*. Within context *AS* sensitivity for stimulus *s1* relates to synapse *S1* and sensitivity for stimulus *s2* to synapse *S2*. Therefore, for example,

$\varphi_{NT,AS}$*(sensitivity(s1, a, high)) = synapsestrength(S1) > B*
$\varphi_{NT,AS}$*(sensitivity(s2, a, high)) = synapsestrength(S2) > B*

However, suppose in a different context *AS'* the connections from the stimuli to neurons *SN1* and *SN2* are switched such as shown in Figure 2 (inspired by the cross-wired brain thought experiment described by Kim, 1996, pp. 115-116).

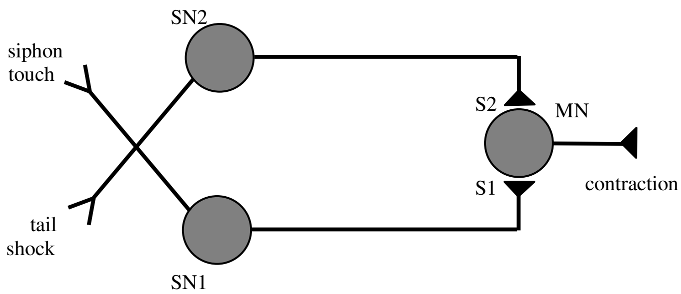

Figure 2: Context *AS'*: cross-wired neural mechanism

Then within context *AS'* the sensitivity for stimulus *s1* relates to synapse *S2*. Therefore for the interpretation mapping related to context *AS'* it holds:

$\varphi_{NT,AS'}$*(sensitivity(s1, a, high)) = synapsestrength(S2) > B*
$\varphi_{NT,AS'}$*(sensitivity(s2, a, high)) = synapsestrength(S1) > B*

This shows by a simple example in what sense the reduction relations depend on the context. The same neural synapse state *S1* relates to sensitity for *s1* in one context, but to sensitivity for *s2* in the other context. Its role fully depends on the context, which can have its own makeup independent of *S1* itself. As within the definition of the interpretation mapping the context is explicitly represented, this situation can be described adequately by distinguishing the two mappings $\varphi_{NT,AS}$ and $\varphi_{NT,AS'}$.

Based on the mapping $\varphi_{NT,AS}$ as defined for basic properties, by compositionality the mapping of more complex relationships is made, for example:

$\varphi_{NT,AS}$*(sensitivity(s, a, high) & observesstimulus(s) → performsaction(a))*
= $\varphi_{NT,AS}$*(sensitivity(s, a, high) & observesstimulus(s))* → $\varphi_{NT,AS}$*(performsaction(a))*
= $\varphi_{NT,AS}$*(sensitivity(s, a, high))* & $\varphi_{NT,AS}$*(observesstimulus(s))* → $\varphi_{NT,AS}$*(performsaction(a))*
= *synapsestrength(S1) > B & observesstimulus(s) → performsaction(a)*

This and other regularities or laws derivable from the cognitive theory *CT* can be mapped onto laws that are derivable from $NT \cup AS$, which illustrates the criterion for interpretation mapping.

Above it was shown how context-dependent interpretation mappings can be applied to the case study. In similar manners the other two context-based approaches can be applied. For example, context-dependent bridge principles for theory *NT* and context *AS* can be defined by (where the path from stimulus *s* to neuron *MN* is via synapse *S*):

$$sensitivity(s, a, low) \leftrightarrow synapsestrength(S) < B'$$
$$sensitivity(s, a, medium) \leftrightarrow B' \leq synapsestrength(S) \leq B$$
$$sensitivity(s, a, high) \leftrightarrow synapsestrength(S) > B$$

Context-dependent functional reduction is applied by taking the joint causal role specification for *sensitivity(s2, a, low), sensitivity(s2, a, medium), sensitivity(s2, a, high)* as follows:

$$C(P1, P2, P3) =_{\text{def}}$$
$$[P1 \,\&\, observesstimulus(s1) \,\&\, observesstimulus(s2) \rightarrow P2] \,\&$$
$$[P2 \,\&\, observesstimulus(s1) \,\&\, observesstimulus(s2) \rightarrow P3] \,\&$$
$$[P3 \,\&\, observesstimulus(s2) \rightarrow performsaction(a)]$$

Discussion

Cognitive theories have a nontrivial dependence on the context of specific (neurological) makeups of individuals and species. Due to this context-dependency, for example, regularities or relationships between cognitive states are not considered genuine universal laws such as laws of Physics or Chemistry, and cannot be directly related to neurological laws: by changing the specific makeup they simply can be refuted. The classical approaches to reduction such as bridge law reduction, functional reduction and interpretation mappings fail to take into account this context-dependency in an adequate manner. One of the proposed alternative approaches for which recently much progress has been made is based on the notion of mechanism; e.g., (Craver, 2001, 2007; Craver and Bechtel, 2007; Glennan, 1996, 2008; Bechtel, 2005ab, 2007, 2008). This approach, which indeed explicitly takes into account a specific makeup in the form of a mechanism, is often positioned as to replace the earlier developed classical reduction approaches.

The contribution of this paper is to show how also these classical reduction approaches can be refined to incorporate the context-dependency in an explicit manner. The context-dependent reduction approaches obtained make explicit in which way laws or regularities in a cognitive theory depend both on neurological laws and makeups. They are not opposed to claims about the different status of psychological laws or regularities, and other claims (such as (a) to (d) in the second section), but work out the implications of these claims in more detail, and as such support them. The detailed formalised definitions of the approaches make it possible to specify specific cases of cognitive theories and how they relate to contexts, as was shown in the case study.

A difference of the context-dependent approaches explored here with approaches based on mechanisms is that for the latter a component-based structure with different levels is assumed, whereas for the context-dependent reduction approaches this structure may or may not be based on components and levels.

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