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CONCEPTS STRUCTURED THROUGH REDUCTION: A  
STRUCTURALIST RESOURCE ILLUMINATES THE  
CONSOLIDATION – LONG-TERM POTENTIATION (LTP) LINK

**ABSTRACT.** The structuralist program has developed a useful metascientific resource: *ontological reductive links* (ORLs) between the constituents of the potential models of reduced and reducing theories. This resource was developed initially to overcome an objection to structuralist “global” accounts of the intertheoretic reduction relation. But it also illuminates the way that concepts at a higher level of scientific investigation (e.g., cognitive psychology) become “structured through reduction” to lower-level investigations (e.g., cellular/molecular neuroscience). After (briefly) explaining this structuralist background, I demonstrate how this resource illuminates an actual, emerging scientific example: the link between the psychological concept of a “consolidation switch” from short-term to long-term memory and the cellular/molecular mechanisms of the transition from early- to late-phases of long-term potentiation (LTP) (an important type of synaptic plasticity in mammalian hippocampus and cortex).

1. STRUCTURALIST BACKGROUND

Historically, structuralists have viewed intertheoretic reduction as a “global” relation. They eschew the “standard” Anglo-American account of theory structure as a set of sentences, propositions, or other linguistic items. But they retain the “standard” idea that reduction is a relation over entire classes of entities that constitute theories (i.e., models). Although structuralists place far stronger restrictions on the reduction relation than Suppes’s (1956, chapters 8 and 9) “isomorphism” condition – see, e.g., Balzer et al. (1987, chapter 6), Mormann (1988), and Mayr (1976) – this “global” feature still leaves the accounts open to Schaffner’s (1967) devastating “too weak to be adequate” challenge (Bickle 1998, chapter 3). There exists, or can be contrived, obvious cases of nonreduction that meet all the formal (set-theoretic) conditions structuralists lay down on the relation.

Although he didn’t mention Schaffner by name, C. U. Moulines (1984) first developed a structuralist resource that can be tailored to address Schaffner’s challenge (Bickle 1998, chapter 3). More interesting for my purposes in this essay, this same resource also illuminates another puzzling metascientific notion. Sometimes in the process of being related to sci-



entific developments in other disciplines (especially “lower-level” ones), concepts from one theory become “structured through reduction”. In the laws or generalizations of the original theory, the concept is characterized *functionally*: as an *entity or process* fully defined by its *causes and effects*, with little or no concern for the underlying mechanisms that yield this functional profile. “Gene expression” in Mendelian through transmission genetics might be a good recent example. This process, characterized in terms of phenotypic ratios and theoretical posits tied directly to these (e.g., “dominance,” “allele”), gets redefined within current molecular genetics in terms of elaborate sequences of molecular and (increasingly) biochemical transcriptional, translational, and recombinant processes (Lewin 1999). However, philosophers of science have not carried an analysis of “concepts structured through reduction” much beyond the vague hints and example just mentioned.

The structuralist concept of theory is an ordered set of classes of models. More precisely, a theory  $\mathbf{T}$  is an ordered triple  $\langle \mathbf{M}_p, \mathbf{M}, \mathbf{I} \rangle$  where  $\mathbf{M}_p$  is a set of *potential models*,  $\mathbf{M}$  is a set of *actual models*, and  $\mathbf{I}$  is a set of *intended empirical applications*. Intuitively, potential models are entities with the appropriate “candidate structure” (defined set-theoretically) to be investigated as actual models of  $\mathbf{T}$  but which may not meet the conditions specified by  $\mathbf{T}$ ’s laws or generalizations. Models are potential models that also meet the conditions specified by the laws or generalizations. Intended empirical applications are “real-world” systems that are expected to be revealed by investigation to be actual models of  $\mathbf{T}$ .  $\mathbf{M} \subseteq \mathbf{M}_p$  and  $\mathbf{T}$ ’s *empirical claim* is that  $\mathbf{I} \subset \mathbf{M}$ , although at any given time for any actual theory  $\mathbf{T}$ , at best  $\mathbf{I} \cap \mathbf{M} \neq \emptyset$ .<sup>1</sup>

To reconstruct actual cases, it is convenient to specify the appropriate classes by defining a set-theoretic predicate. Consider a simple example: the theory of classical collision mechanics ( $\mathbf{CCM}$ ). We define:  $x$  is a (model of)  $\mathbf{CCM}$  iff there exist  $P, T, v, m$  such that

- (1)  $x = \langle P, T, \mathfrak{R}, v, m \rangle$
- (2)  $P$  is a finite, nonempty set
- (3)  $T$  is an ordered pair set  $\langle t_1, t_2 \rangle$
- (4)  $v : P \times T \rightarrow \mathfrak{R} \times \mathfrak{R} \times \mathfrak{R}$
- (5)  $m : P \rightarrow \mathfrak{R}^+$
- (6)  $\sum_{p \in P} m(p) \times v(p, t_1) = \sum_{p \in P} m(p) \times v(p, t_2)$

On the standard interpretation  $P$  is a set of particles,  $T$  a set of time instances ( $t_1$  before,  $t_2$  after the collision),  $v$  is the velocity function,  $m$  is the mass function, and (6) specifies the law of conservation of momentum before and after the collision. The class  $\mathbf{M}_p(\mathbf{CCM})$  contains all those structures (“real world” and “purely mathematical”) that meet conditions (1)–(5). To use Stegmüller’s (1976) helpful phrase, these are the structures “about which it makes sense to ask” whether they are actual models of **CCM**.  $\mathbf{M}(\mathbf{CCM})$  contains all those members of  $\mathbf{M}_p(\mathbf{CCM})$  that also meet lawful condition (6).  $\mathbf{I}(\mathbf{CCM})$  contains all the “real world” systems we expect to be confirmed empirically to meet conditions (1)–(6).

Intertheoretic reduction can then be specified as a relation  $\rho$  whose domain is  $\mathbf{M}_p(\mathbf{T}_B)$  (where  $\mathbf{T}_B$  is the “reducing” or “base” theory) and whose range is  $\mathbf{M}_p(\mathbf{T}_R)$  (where  $\mathbf{T}_R$  is the “reduced” theory). Structuralists and their sympathizers have proposed a variety of conditions restricting  $\rho$  (see especially Balzer et al. 1987, chapter 6; Mayr 1976; and Bickle 1998, chapter 3). However, despite the increasingly sophisticated set-theoretic conditions and applications to historical cases, Moulines pointed out the essential flaw with such “global” accounts:

For a complete picture of a reductive relationship between two theories, one has to take into account some sort of relation between the respective domains. Otherwise, when confronted with a particular example of a reductive pair, we would feel that all we have is an *ad hoc* mathematical relationship between two sets of structures, perhaps by chance having the mathematical properties we require of reduction but not really telling us something about “the world.” ... The possibility that we find a formally appropriate  $\rho$  just by chance or by constructing it in an *ad hoc* way cannot be ruled out in general. ... I think we would feel that such a reduction is not “serious”. (1984, 55)<sup>2</sup>

According to Moulines, this problem arises because  $\rho$  is defined “too globally”, i.e., as a relation over entire sets of potential models comprising theories. But we can take our structuralist analysis of theories “down a level” (so to speak), to the constituents of individual potential models.  $\rho$  can then be construed as constructed, at least in part, out of cross-theory *links* between (some of) these “ontological” constituents.

Any  $x \in \mathbf{M}_p(\mathbf{T})$  will have the following general form:

$$x = \langle D_1, \dots, D_n, A_1, \dots, A_m, r_1, \dots, r_p \rangle$$

where the  $D_i$ s are the “real” base sets, the  $A_i$ s are auxiliary base sets (formal or mathematical spaces), and the  $r_i$ s are relations or functions typified by the base sets (i.e., constructed out of the base sets using possibly repeated operations of power set and Cartesian product) (Balzer et al. 1987, chapter 1). In the **CCM** example,  $P$  and  $T$  are “real” base sets,  $\mathfrak{A}$  is an auxiliary base set, and  $v$  and  $m$  are relations typified by  $P$ ,  $T$ , and  $\mathfrak{A}$ .

Consider now a  $\rho \subseteq \mathbf{M}_p(\mathbf{T}_B) \times \mathbf{M}_p(\mathbf{T}_R)$ . Moulines (1984) defines  $\rho$  as an *ontological reduction link* (ORL) just in case  $\rho$  meets all the conditions on the reduction relation and is partly composed of relations between the  $D_i$ s constituting the potential models of  $\mathbf{T}_R$  and at least some of the  $D'_j$ s constituting the potential models of  $\mathbf{T}_B$ . There are two types of ORLs. *Homogeneous* ORLs are total or partial identity relations between the base sets: total when the  $D_i$  is identical (in the extensional, set-theoretic sense) with some  $D'_j$ , partial when the  $D_i$  is identical with some proper subset of some  $D'_j$ . *Heterogeneous* ORLs link at least one real base set of  $\mathbf{T}_R$  to one or more of  $\mathbf{T}_B$  in a way that does not imply identity of elements. A global reduction link  $\rho$  can be composed entirely of homogeneous ORLs, entirely of heterogeneous ORLs, or of some combination of both types. Moulines calls the last type *mixed (ontological) reduction* and insists that “in real science ... it is likely that mixed reduction is the most frequent case” (1984, 60). He cites the rigid body mechanics-to-Newtonian particle mechanics and Newtonian particle mechanics-to-special relativity theory reductions as accomplished mixed cases. In the first, although the base sets of space points and time points are linked homogeneously across the two theories, elements of the set of rigid bodies do not belong to any base set in the reducing theory. The base set of rigid bodies is linked heterogeneously with the base set of Newtonian particles. And in the second case, the set of particles is linked homogeneously across related potential models of the two theories, but elements of the separate Newtonian base sets of space points and time points don't belong to any base sets of special relativity. The former get linked heterogeneously to the base set of Minkowskian spacetime points. Moulines also points out a number of reductions “in progress” that appear to be either mixed or completely heterogeneous, including simple thermodynamics of gases-to-kinetic gas theory (see Bickle 1998, chapters 2 and 3 for further work on this example), wave optics-to-classical electrodynamics, and Mendelian genetics-to-molecular biology (1984, 60–62).

Heterogeneous reductions come in a number of varieties. The simplest relates a  $D_i$  of  $\mathbf{T}_R$  to a single  $D'_j$  of  $\mathbf{T}_B$ . More complex examples include those that relate a single  $D_i$  to a *sequence* of elements from some  $D'_j$ , to a sequence of elements from several base sets  $D'_1, \dots, D'_j$ , or even to a sequence of elements from several base sets and relations  $r'_1, \dots, r'_m$  of  $\mathbf{T}_B$ . Moulines points out that these complexities arise in initial structuralist attempts to reconstruct the Mendelian genetics-to-molecular biology reduction: “If  $D_i$  is the set of genes of an organism and  $D'_j$  a certain set of organic molecules, then to each gene a sequence of organic molecules is supposed to correspond biunivoquely” (1984, 64). Elements of the base set

of genes, however, don't belong to any base set of organic molecules. And if we attempt to reconstruct the reduction of Mendelian/transmission theory of gene expression (a process) to molecular/biochemical mechanisms, the base sets of the former will be heterogeneously linked to both base sets and relations from molecular biology.

Structuralists typically think of a theory's relations and functions as *typifications*, constructions out of the real and auxiliary base sets using only repeated applications of power set and Cartesian product. This makes it unnecessary to specify ORLs for the reduced theory's relations and functions, and implies that heterogeneous ORLs that link a base set of  $T_R$  to a combination of base sets and relations/functions of  $T_B$  is "reducible" in principle to one that links the former only to some sequence or combination of the base sets of  $T_B$  (Moulines 1984, 66–67). But we need not assume so conservative a view of theory relations and functions. Some are clearly typifications (especially in mathematical physics, the "natural home" of the structuralist approach). But for "process-focused" sciences like genetics, molecular biology, psychology, and physiology, we might need to treat some theoretical functions more on a par with base sets. They can then be constituents in genuine ("unanalyzable") ORLs. The formal definitions that Moulines (1984) provides of homogeneous and heterogeneous ORLs could be extended easily to accommodate this view.

ORLs add a condition on structuralist reduction concepts that enable them to overcome Schaffner's "too weak to be adequate" challenge. Both actual and "contrived" cases that meet the mathematical conditions on the reduction relation  $\rho$  but which aren't genuine reductions will not be genuine ORLs: such links will not obtain across the base sets in the intended empirical applications of the two theories (Bickle 1998, chapter 3). But in heterogeneous cases where some base set of  $T_R$  gets linked to a sequence of elements from base sets and relations from  $T_B$ , we also get an account of what it is for "the amorphous basic entities of the reduced theory [to] become structured through reduction" (Moulines 1984, 67–68). An entity (or process, in light of the previous paragraph), characterized entirely by way of the relations and laws/generalizations of  $T_R$ , comes to be related *in a domain eliminating way* to sequences of entities and processes characterized by the relations and laws/generalizations of  $T_B$ . There are no rigid bodies, separate space points and time points, or Mendelian genes, at least not in the way that there remain particles in special relativity theory and planets in Newton's celestial mechanics. The former aren't part of the way that the  $T_B$  "carves up the world": although the roles that these base sets play in the relations and laws/generalizations of  $T_R$  might bear interesting structural similarities to the roles played by the base sets (and

possibly theoretical relations and functions) in  $T_B$  to which they are linked by heterogeneous ORLs.

## 2. THE CONSOLIDATION-LTP LINK<sup>3</sup>

Armed with this structuralist resource, I next turn to a recent development across psychology and neuroscience. My hope is that the structuralist resource developed above can illuminate an emerging intertheoretic link. Since the seminal work of Ebbinghaus, Müller, and Pilzecker in the 1880s, and elaborated by James in his classic *Principles of Psychology* (1890), psychologists have distinguished *short-term* from *long-term memory*. The former is transient, lasting anywhere from the immediate present to several minutes (“working memory”) up to an hour or more with rehearsal. The latter is stable, lasting for weeks, months, years, sometimes even decades, and typically requires stimulus repetition to induce this stability. Furthermore, as Müller and Pilzecker demonstrated experimentally more than one century ago, the conversion from short-term to long-term memory can be disrupted by *retrograde interference*: distractions introduced *after* the initial items had been stored in short-term memory. They coined the phrase *consolidation period* to refer to the time needed for the short-term “memory trace” to achieve stable long-term form.

Other than careful exploration of the time course of consolidation for different memory items, the nature and timing of effective retrograde interference, and the amount of repetition required to convert short-term to long-term memory, psychologists have been unable to explain satisfactorily the *consolidation process or switch*. Recent neuroscience has made greater progress. Pharmacological manipulations dating back nearly forty years have produced animals (including mammals) with intact learning and short-term memory capacities but profoundly deficient long-term memories. Over the past decade, in keeping with biotechnology’s expansion, these manipulations are now carried out using genetic knockout and transgenic rats and mice.

The current state of theory about learning and memory in “mainstream” neuroscience follows a lead first developed by Donald Hebb in his classic book, *The Organization of Behavior* (1949). (By “mainstream” neuroscience I mean the “Society for Neuroscience” crowd, to be distinguished for the most part from self-described “cognitive neuroscientists”). Hebb recommended that we think of learning and memory in terms of *synaptic strength* and *plasticity*: the changeable effect that a given neuron has on inducing a change in membrane potential in neurons with which it shares an active synapse. Mammalian *long-term potentiation* (LTP), a type of syn-

aptic plasticity now documented in hippocampus, cerebellum, and cortex, is a promising candidate for the cellular mechanism of certain types of long-term memory. It is rapidly induced, specific only to activated synapses (“associative”), enhanced by repetition, lasts for as long as can be measured, is selectively blocked by treatments that block behavioral learning, and is induced by physiological inputs that also give rise to learning in behaving animals.

Recent work by Eric Kandel and his colleagues has examined LTP in the Schaffer collateral pathway of the rat hippocampus. The hippocampus is a bilateral structure in the subcortical medial temporal lobe. It is known to play a crucial role in long-term memory storage and access. Hippocampal ablation in experimental animals produces little deficiency in initial learning and short-term recall, but profound deficits on certain types of long-term recall tasks. The human neuropsychological syndrome of global amnesia results from bilateral damage to hippocampus (and some surrounding tissue in the medial temporal lobe). Medial temporal lobe amnesics, like their experimental animal counterparts, have intact short-term memory but profound long-term memory deficits for “declarative” items (Squire 1987). The Schaffer collateral pathway is a bundle of axons from cells in the hippocampal CA3 region that project excitatory synapses to the hippocampal CA1 region. This has been a common site for studying LTP for nearly thirty years.

Kandel and his colleagues found evidence for two distinct phases of LTP. The early phase (E-LTP) begins immediately after a single high-frequency electric pulse train to the pre-synaptic axon and lasts from one to three hours. Increased glutamate release (an excitatory neurotransmitter) by the stimulated presynaptic neuron binds to postsynaptic AMPA receptors ( $\alpha$ -amino-3-hydroxy-5-methyl-4-isoxazole propionic acid) that directly open  $\text{Na}^+$  (sodium ion) gates. This produces enhanced depolarization of membrane potential in the vicinity of the bound receptors, releasing voltage gated  $\text{Mg}^{++}$  (magnesium) ions that under normal membrane potentials block NMDA (N-methyl-D-aspartate) postsynaptic receptors. Unblocked NMDA receptors open gates for  $\text{Ca}^{++}$  (calcium ion) influx into the postsynaptic cell. Increased intracellular  $\text{Ca}^{++}$  concentration activates a  $\text{Ca}^{++}$ -calmodulin cascade that in turn activates a set of protein kinases (enzymes) that (1) phosphorylate AMPA receptors, making them even more efficient gates for  $\text{Na}^+$  influx, and (2) drive the production of *retrograde transmitters* (from post- back to presynaptic cell). One of these, nitric oxide (NO), is a gas that readily diffuses across cell membranes but has a very limited diffusion area and is only active in presynaptic terminals releasing glutamate. Although its mechanisms of action are not yet entirely

clear, NO enhances glutamate release from presynaptic terminals. The result of these activity-driven cellular mechanisms is a sharp increase in transmission capacity at affected synapses, measurable from roughly one up to three hours.

The late phase of LTP (L-LTP) requires a series of electric pulse trains to the presynaptic axon (the laboratory analog of “repetition” known from psychological studies to be important for consolidation to long-term memory!). This increases further the rate of postsynaptic  $\text{Ca}^{++}$  influx through the open voltage-gated NMDA receptors and in turn the amount of  $\text{Ca}^{++}$ -calmodulin. The latter, in conjunction with a second messenger receptor activated by input from modulatory interneurons, activate G proteins in the postsynaptic cell that convert ATP molecules (adenosine triphosphate) into cAMP (cyclic adenosine monophosphate). cAMP binds to the regulatory subunits of PKA (protein kinase A) molecules, freeing the catalytic subunits. In sufficient numbers, these freed PKA catalytic subunits translocate into the postsynaptic cell nucleus, where they have two principal effects. First, they phosphorylate CREB-1 (cAMP-response element binding protein-1), enabling this molecule when bound to CRE (cAMP-response element), a subregion in the regulatory region of two important classes of *immediate early genes*, to initiate transcription of regulatory proteins that both maintain the PKA in a persistently active state and lead to the growth of new postsynaptic receptor sites. Second, by interacting with MAP kinase (mitogen-activated protein kinase) in the cell’s nucleus, the catalytic PKA subunits inhibit CREB-2 (cAMP-response element binding protein-2). CREB-2 is an inhibitory transcription regulator (a “repressor”). It is thought to inhibit the facilitating action of CREB-1 at the two classes of immediate early genes by binding to both the CREB-1 molecule and the CRE regulatory subregion. The PKA-MAP kinase interaction blocks CREB-2’s repressive effects.

In a nutshell, the “consolidation switch” of psychology yields to a three-part sequence of processes described within contemporary cellular and molecular neuroscience: the activity-induced enhancement of PKA leading to (1) increased binding of CREB-1 to CRE regulatory subregions on a class of immediate early genes that transcribe regulatory proteins for persistently active PKA and another class that transcribes proteins needed for the growth of new postsynaptic sites; (2) the inhibition of CREB-2, a transcription repressor for these immediate early genes; and (3) the production of protein products transcribed by these immediate early genes. L-LTP requires new gene transcription and protein synthesis. The biochemistry of affected neurons changes permanently when L-LTP is induced, enhancing the probability of successful neural transmission for long periods. What

psychologists call “retrograde interference” turns out to be any process that interferes with any of these steps after initial (repeated) stimulus presentation.

But is L-LTP really the mechanism for long-term memory in behaving animals? Work with gene knockout mice and an ingenious behavioral paradigm shows convincingly that it is. Kandel’s group generated mutant mice partially expressing a gene that blocked the action of the catalytic subunit of PKA. Rusiko Bourtchouladze and Alcino Silva studied mice in which the gene expressing CREB-1 was partially knocked out. In both groups the transgene or knockout was specific to hippocampus. Both groups along with controls were subjected to a novel environment for two minutes, followed by a sound (CS) for thirty seconds, followed by a foot shock (US) for 2 seconds. When placed back in the same box a few minutes later, normal mice display a defensive reaction (freezing); memory for environmental cues requires an intact hippocampus. Similarly, normal mice will freeze to the tone when it is presented a few minutes later in any context; this type of CS-US fear conditioning requires an intact amygdala (another bilateral structure in the subcortical medial temporal lobe). Both types of genetically altered mice learned both tasks as easily as normal mice and still showed normal freezing to the environmental cues and the CS when tested one hour after initial training. But 24 hours later, unlike normals, both groups of genetic mutants showed no freezing to the environment. They were deficit in a long-term memory task that requires the hippocampus. But they displayed normal freezing 24 hours later to the CS. They were intact on a long-term memory task that requires the amygdala (a region where the transgene was not expressed). On the other hand, normal mice given a protein synthesis inhibitor after initial training that acts on both hippocampus and amygdala are deficient at both long-term memory tasks. Manipulating steps in the process that yields L-LTP not only blocks that cell-physiological/molecular process. It also produces selective deficits in long-term memory.

From the structuralist background presented above, what can we say about the LTP-consolidation link? Cognitive psychology, through its base sets, fundamental and derived theory relations and functions, and generalizations in terms of these, characterizes an entity/process, the consolidation switch. But it does so only in terms of the time course and amount of repetition needed to convert a given type of memory item from short-term to long-term memory (with the latter concepts also characterized primarily in terms of duration of recall after initial presentation) and the behavioral efficacy of different types of retrograde interference. In other words, psychology characterizes this entity/process in purely functional fashion, with

little regard for the *causal mechanisms* generating this functional profile. The link between this base set or process and those containing the cellular/molecular sequences signaling the transition from E-LTP to L-LTP and the maintenance of the latter is a heterogeneous ORL. The elements of the former are not even elements of partial subsets of the latter. Cellular and molecular neuroscience “carves up the world” in a fundamentally different way than does cognitive psychology, even though the intended empirical applications of the two theories overlap significantly: the two theories are intended to apply to roughly the same set of “real world” systems.

### 3. CONCLUSION

From the structuralist perspective articulated here, is there any such thing as “psychology’s consolidation switch”? No, in the sense that neither that concept nor its affiliated ontology within cognitive psychology are among the base sets and fundamental theory relations and functions of contemporary cellular and molecular neuroscience. But the emerging cellular/molecular story nevertheless still puts its constituents together into a structure abstractly similar (at a coarse-grained level) to psychology’s functional concept. The sequence of cellular/molecular mechanisms even explains the sort of behavioral data that psychologists use to study the duration of the consolidation process and methods of retrograde interference. In an important sense, cognitive psychology’s notion of a consolidation switch is an important functional *approximation* of the cellular/molecular mechanisms that signal the switch from E-LTP to L-LTP and maintain the latter.

So do we here have cross-theoretic identification or elimination? Based on the application of the structuralist resource presented above, I am inclined to answer the latter. But the answer we give to that question is less important than the project of clarifying intertheoretic links, both “global” and “local,” in interesting scientific cases. The question now strikes me as “metaphysical” in the perjorative logical-positivist sense. On the other hand, structuralist philosophy of science provides fruitful resources for addressing the significant metascientific project.

### NOTES

1. This is a simplification of the structuralist concept of *theory-element*, the simplest concept that corresponds to one of the meanings of “theory.” It is common in structuralist writings on intertheoretic relations to work with this simplification. (Moulines 1984 uses it in the original paper where he develops the resource I am about

- to explain.) For the full structuralist account of theory and the relation between theory-element and theory, see Moulines (1996) and Balzer et al. (1987, chapter 1).
2. Compare Moulines's worry with Schaffner's well-known critique of Suppes's Reduction Paradigm, which like structuralist accounts treated reduction as a relation across "global" theories characterized set-theoretically: "Different and nonreducible (at least to one another) physical theories can have the same formal structure – e.g., the theory of heat and hydrodynamics – and yet one would not wish to claim that any reduction could be constructed here" (1967, 143). In Bickle (1998) I call this the "too weak to be adequate challenge" to this approach to reduction.
  3. A good introduction to the scientific details presented in this section is Squire and Kandel's (1999). It is the best nontechnical treatment of neuropsychological and neurobiological work on memory that is available today. Squire is one of the world's leading neuropsychologists and Kandel recently shared the 2000 Nobel Prize for Physiology and Medicine for his work on the cellular and molecular basis of learning and memory. Together they cover the full range of levels at which memory is researched. All the scientific details I present below are at least mentioned in that book, primarily in chapters 6 and 7. However, the book has only a short list of further readings for each chapter. For those seeking a deeper level of scientific detail or a more extensive reference list, consult the chapters in the last part of Kandel et al. 2000.

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