Chapter 13

The Partitioning and Structuring Problems

§ 1. The Partitioning Problem in Psychological Context

In chapter 12 it was pointed out that when the same input vector X is applied to a multiplicity of adaptive Instar maps, some mechanism must exist for determining which Instar or Instars, *if any*, will respond to the input by adapting their weights. The problem of coming up with such a mechanism is what we will here call "the partitioning problem."

The precise mechanism by which the partitioning problem is solved in a network system model will determine how well the system deals with the stability-plasticity dilemma. Closely tied to this issue is another, which neural network theorists are fond of calling the "noise sensitivity" of the network system. As it happens, this usually ill-defined notion of "noise" in a network system makes an excellent starting point for discussing what some, including your author, regard as *the* primary research problem in network system level biological signal processing. This chapter is about that problem.

What is "noise"? To a system theorist, the general term denotes any "undesired" signal. In systems of Weinberg's region II and region III classes (chapter 7), where the statistical expected value of a quantity is usually the most important kind of signal variable, "noise" is usually used to refer to deviations from the expected value. This is the usage of the term "noise" employed, for example, by most electrical engineers. The usage fits with our principal definition ("noise is any undesired signal") because, intellectually at least, deviations from what is to be expected are "undesirable" in the eyes of a theorist. In terms of the space-partitioning/prototype-vector way of looking at adaptation presented in chapter 12, "noise" would be the deviation, $X - W$, between an input vector X and its "prototype" W.

But these *statistical* ideas of what is to be considered "noise" are merely mathematical definitions which happen to have an easily-quantifiable means of expression. Regardless of how "undesirable" a signal in its mathematical form may seem to a theorist, what is *really* the *proper* context of the term "undesirable" so far as neuroscience (not merely computational neuroscience) is concerned? It should not be tacitly presumed that what is "undesirable" in a signal to someone dealing with the technical applications of *artificial* neural network systems is also "undesirable" so far as *brain function* is concerned. At the level of map and network system models, the models are proposed with a purpose in mind, namely *to obtain a theoretical understanding of* *psychological phenomena in terms of brain function*. Within the context of this purpose, it is perhaps obvious to the reader that the meaning of the word "undesirable" (and, therefore, "noise") is not so clear. Consequently, the issue is: How are we to understand the idea of "noise" in a ***neuropsychology*** context?

This is not yet a particularly well-posed question at the current state-of-the-science in neuroscience. Fortunately, there are two complementary pathways by which we can explore this question and put it into a workable context for computational neuroscience and biological signal processing. On the one hand, the ground for understanding psychological phenomena is through the experimental examination of the behaviors of the psychological subject, i.e. the animal or person being studied. Let us recall that *all* the primary objects of psychology – cognition, emotion, consciousness, etc. – are supersensible objects. In contrast, behaviors are observable, open to experimental study, and capable of being correlated against brain activity through such means as PET scans, fMRI scans, and the like. Behavior includes the self-reports made by human subjects during psychology research, by means of which the psychologist can pry into the otherwise autistic world of "feelings", "moods", "drives", etc.[1] All this does not mean we will take the long-discredited road traveled by the behaviorists in early twentieth century American psychology; but it does mean the study of behavior is one pathway by which we can approach the issue at hand.

The second pathway is by means of examining the psychological role of adaptation. Here we must distinguish between two usages of the word "adaptation." In the first usage, adaptation refers to the final outcome of the act of adapting. In the second usage, adaptation refers to the process of adapting. The making of an adaptation (the second usage) is open to examination by means of observable actions. Because all organisms undertake adaptation responses to their environments, it is not unreasonable to take the point of view that the outcome of an adaptation process is in a real sense a "purpose" of the organism *served by* the process of adaptation, regardless of whether or not this purpose is a "conscious purpose" (which it usually is not).

§1.1 Behaviors and Psychological Meaning

A behavior is called ***voluntary*** if it is neither autonomic nor the result of a reflex response (such as the various reflex responses produced by the neural organization of the spinal cord). When the behaving subject is a human being, activity signals within the central nervous system related to voluntary behavior can be said to be representations that "hold a meaning" for the

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[1] By "autistic" we do not here refer to the pathology known as autism. Rather, we use the word in an older and broader context. A mental representation is said to be "autistic" if the subject finds him- or her-self unable to communicate this representation to another person in a way that second person can adequately understand. Piaget introduced this usage of the term to developmental psychology.

subject. It is a bit more problematical but not too great a leap to assume the same would be true for animal subjects, at least at the higher phylogenetic scale of evolution. But what, to a neuroscientist, does "meaning" mean? That is, what observable phenomena do we have at hand to which we can apply the word "meaning" with some degree of scientific rigor? If we can answer this question, then we can extend and apply this understanding to biological signal processing at the network system level in order to distinguish between a "meaningful signal" and a "meaningless signal." The latter type of signal *should then have no non-pathological implications for behavior* and, in this technical sense, could be regarded as a "noise signal" in the context of neuropsychology.[2] If such a signal did result in pathological behavioral consequences, the network system would then be said to be ***non-robust*** to the presence of this signal.

At the end of his life, Piaget and his co-workers were researching this issue of understanding what scientific definition should be attached to a psychological theory of meaning. To put this another way, as an object of psychology "meaning itself" is a supersensible object, and Piaget et al. were working on tying this idea to observable phenomena that could be regarded as signifiers of the presence of "meaning." Death took him before Piaget could complete his work, but not before some fundamental groundwork had been laid. Piaget called this theoretical foundation ***the logic of meanings*** [PIAG17]. Bärbel Inhelder, Piaget's long-time colleague and collaborator, wrote in the introduction of Piaget's last book,

> Piaget intended to bring to light the very roots of logic by going back to implications between sensorimotor actions. Such a logic could only be a logic of meanings where implications are not restricted to statements: in the subject's view, every action or operation is endowed with meanings; therefore, one may deal with systems of implications among the meanings of actions, and then among the meanings of operations. Provided that the meaning of actions and the causality of actions are carefully distinguished, the subject's expectations and anticipations about the chaining of actions bear witness to the existence of early inferences. Hence a privileged form of inference is the action implication, which is an implication between the meanings of actions [PIAG17: vii-viii].

A "meaning" is something – some mental representation – the subject infers in relationship to his sensational perceptions or his practical actions. Rolando Garcia, Piaget's collaborator on this last project, tells us,

> Meanings result from an attribution of assimilation schemes to objects, the properties of which are not "pure" observables but always involve the *interpretation* of the "data." In accordance with the classic definition of schemes ("a scheme is what can be repeated and generalized in an action"), we shall say that the meaning of an object is "what can be done" with the object, and this definition applies not only to the sensorimotor level but to the pre-operatory level starting with the semiotic function. However, meanings are also what can be said of objects, i.e.

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[2] Network system level signals that serve autonomic, reflex, and homeostasis functions can be said to be ***functionally meaningful*** in the sense that behavioral responses of these types are understood through understanding these signals and the signal processing applied to them.

> descriptions, as well as what can be thought of them, when classifying or relating them and so on.
>
> As for actions themselves, their meaning is "what they lead to" according to the transformations they produce in the objects or situations on which they bear. Whether predicates, objects, or actions are involved, meanings imply that the subject's activities interact either with an external, physical reality, or with a reality the subject himself has previously generated, as in the case of logico-mathematical entities [PIAG17: 159-160].

Piaget himself said the meaning of meanings, "is that they are only instruments for understanding, in contrast with mere observations which, before being endowed with meanings, can only provide extensions devoid of any intelligibility" [PIAG17: 120]. What is perhaps the key and basic finding coming out of this last study is that "meaning" takes its root and point of origin from the infant's practical experience with his own actions and their outcomes. The earliest meanings, which are the point of origin for all later meanings that can be verbalized after the development of speech and the semiotic function of thought, are tied inextricably to the subject's early sensorimotor action schemes (which themselves develop as habits from the most primitive reflex actions with which the baby is equipped at birth).

> As a conclusion, we shall classify the various forms of meanings and meaning implications. To begin with, the simplest are the meanings of predicates. They may be defined as the similarities and differences between one property observed in an object and other predicates that are recorded simultaneously or already known.
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> It follows that an object is a set of conjoined predicates and its meaning amounts to "what can be done" with it, and is thus an assimilation to an action scheme (whether the action is overt or mental). As for actions themselves, their meaning is defined by "what they lead to" according to the transformation they produce in the object or in the situations to which they are applied. Whether we are dealing with predicates, objects, or actions, their meanings always implicate the subject's activities, which interact either with an external reality, or with elements previously generated by the subject [PIAG17: 119-120].

"Meanings" are therefore the binding elements for assimilation and for the coordination of Piagetian schemes.

> In the first place, we have been led to replace the classical extensional implication [of symbolic logic] by what we have called the "meaning implication" $A \rightarrow B$, in which at least one meaning of B is embedded in A, and thus this "inherence" relation is transitive . . .
>
> The import of this definition of meaning implication is that, since any action, in addition to its causal aspect (i.e., its being actually carried out), has a meaning, there must be implications between actions, that is to say between their meanings. This is a fundamental reality, going far beyond the realm of implications between statements, and manifested from the beginning of what we have called the logic of actions, which is the necessary basis of operatory logic.
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> Before discussing the relations between these two logics, let us first notice that an action implication, just as implications between statements, may take three forms: (1) a "proactive" form . . . in which case $A \rightarrow B$ means that B is a new consequence derived from A; (2) a retroactive form . . . according to which B implies A as a preliminary condition; and (3) a justifying form, which relates (1) and (2) through necessary connections that thus attain the status of "reasons."
>
> These various initial relations, first separately and then through combinations, serve to constitute fragments of structures that progressively become coordinated until "groupings" are

> formed beginning at about age 7-8 years. The early skeletal structures emerging from interactions among meanings are all the more interesting because they prepare, not only for the formation of concrete operational groupings, but also for the more complex 16 operations found at the formal level, which correspond to the 16 connectives of truth tables, if these are interpreted in terms of meanings and not in their purely extensional form. Thus, we have witnessed the early establishment of intersections, incompatibilities, and so forth, but at the level of actions rather than of statements. This again demonstrates the general formative role of the logic of actions and action implications in the origination of meaning implications [PIAG17: 120-121].

These descriptions do not tell us the details of how all this is implemented during the development of human intelligence; this we will take up in the following subsection. What we see in the quotes above (and which is brought out more concretely in the experiments documented in [PIAG17]) is more along the lines of "what happens" rather than "how it happens." In this discussion of the origination of early structures and their later elaboration through coordinations of these "fragments," it is perhaps not too difficult to imagine this psychological phenomenon in terms of a network system structure counterpart in brain organization, or to at least imagine such a corresponding model is possible to deduce. If we draw back some fair distance from the wealth of detail provided by modern anatomical and physiological findings, returning to the vision of McCulloch and Pitts and their finding that networks of McCulloch-Pitts "neurons" are capable of instantiating the statements of formal propositional logic [McCU], one should be able – with sufficient imagination – to envision the structure-forming process described above in caricature form as the assembling of McCulloch-Pitts logic networks. The fact that Piaget et al., over the course of many years of experimental research, were able to trace the development of formal logical thinking back to an earlier "proto-logic" of action and meaning implications testifies to this possible neurological interpretation for the psychological findings.

There is, however, an issue with which we must deal. If a meaning is "what is similar or different between two properties" or "what an action leads to" or "what can be done with an object," how are we to understand the *possibility* that such meaning implications can be made by an infant still too young to conceive of permanent objects or even to know that his body is his own? Piaget's own research makes it convincingly clear this knowledge is a long time in coming, requiring an extensive "apprenticeship" during the sensorimotor stages of development (birth to about age 2 years). Whatever may be the foundation of meaning implications, this "whatever" *cannot* be an *objective* foundation because the new-born infant has no innate concept of objects. Rather, the conception of objects is an *outcome* of the structuring process, not the basis for it. Human beings do not possess a "copy of reality" mechanism.

If the foundation cannot be objective, then all that is left is for it to be *subjective*. Piaget made many comments all pointing to the role of ***affective perceptions*** in the development of objective intelligence. Although he never formulated a complete and systematic theory of affectivity and its role in the development of intelligence, he did provide the beginnings of such a theory [PIAG18]. This text will not pursue the details of this here, nor digress into the still-unsettled arenas of emotion psychology and motivational psychology, but it will state an overarching encapsulation: The many affective perceptions to which Piaget alludes in his many works can be classified under two headings, the general "flavor" of which Kant captured with two of his technical terms, *Wohlgefallen* and *Mißfallen*. These words, little used in modern German, roughly translate into English as "satisfaction" and "dissatisfaction." However, in their 18th century usage, the connotations of these words do not quite match those of their English language counterparts. *Wohlgefallen* is "satisfaction" in the sense of "oh, this is not bad." Likewise, *Mißfallen* carries the connotation of "oh, this is not good." This is perhaps the best we can do in putting into words the "flavor" of these subjective *feelings*.

In neurological terms, the affective factor underlying the possibility of meaning implications points to a role for the limbic system of the brain (the part of the brain implicated in the experience of emotions, moods, etc.). This has its counterpart in neural network theory in the idea of an actor-critic network organization [WIDR8], [BART1-2], an idea briefly mentioned in chapter 12. The affective factor is something we must bear in mind as we move on to consider general adaptation, to which we turn next.

§1.2 Adaptation and Equilibration

The word *adaptation* has several different and somewhat specialized usages in psychology, biology, and neural network theory. All refer to either change of one kind or another in the organism or the system to which the term is being applied, or to the end result of that change. Even dictionaries disagree on the number of different definitions for the term. Biology makes distinctions between evolutionary adaptation, physiological adaptation, and sensory adaptation. Reber's *Dictionary of Psychology* adds two more distinctions for experimental psychology and social psychology. Widrow and Stearns [WIDR7] define an *adaptive automaton* as "a system whose structure is alterable or adjustable in such a way that its behavior or performance (according to some desired criterion) improves through contact with its environment."

In many of the less specialized definitions of adaptation this factor of "some desired criterion" is present. For example, evolutionary adaptation in biology is recognized in terms of natural selection. Specifically, a change is regarded as an adaptation if: (a) it better fits the organism in its environment; (b) it occurs commonly in the population; and (c) the cause of its commonness is natural selection. On the other hand, in experimental psychology the term is used to denote a change in the responsiveness or sensitivity of a sensory receptor or sense organ that is temporary in nature. The origin of this usage is clearly linked to psychophysical studies and lacks something of the quality of the term as adaptation is used by Widrow and Stearns or by evolutionary biologists.

This leads us to inquire if there might be some better definition of adaptation applicable to psychology and more closely attuned to the usage of this term in neural network theory. The answer is "yes" and the definition is provided by Piaget: ***Adaptation is an equilibrium between assimilation and accommodation***. To understand this definition, we must understand the terms assimilation, accommodation, and equilibration.

Generally speaking, assimilation means *to take in, absorb, or incorporate as one's own*. When specifically applied to developmental psychology, assimilation is said to have occurred when a scheme is successfully applied to a particular object or event. A scheme, as we will recall from above, is that which can be repeated and generalized in an action, whether this action is physical (as in a movement) or mental (as in a reasoning *process*). Piaget was able to identify three levels of assimilation that develop successively in children. The first and most basic is ***reproductive assimilation***, where the child is able to successfully repeat the same action in response to a stimulus, object, or environmental condition. The second form which appears is ***recognitory assimilation***, which is revealed by the child's ability to detect differences between objects or events and respond with discriminative actions based on these differences. The third and highest form of assimilation is ***generalizing assimilation***, which is revealed by the child's ability to note similarities between different objects or events and to incorporate them into general classes and categories.

Accommodation is the modification of a scheme to make it fit a new situation. However, such a modification is subject to a very special requirement, namely that the accommodated scheme must still retain its original capacities for assimilation. If I already have a grasping scheme capable of grasping a ball, and I accommodate this scheme so that I can grasp a pencil, the accommodation leaves me still able to grasp a ball. Put in more general terms, accommodation takes a scheme structure S_1 and produces a new structure $S = \{S_1, S_2\}$ in which S_1 and S_2 are now differentiated substructures under a *total* scheme structure S. Here it is important to remember that a ***structure*** is a system of self-organizing transformations, these transformations exhibiting the property of closure in the sense that no new element engendered by their operation breaks the boundaries of the system. A structure is a *totality*, and accommodation preserves the totality of the structure while at the same time modifying it when producing the differentiations within its substructures.

It is this *conservation of the totality of the structure* that distinguishes accommodation from adaptation as the latter term is used in automaton theory. In an adaptive automaton, one possible outcome of an adaptation algorithm can be loosely described as "forgetting." This is to say that a neural network classifier that once was able to successfully classify a specific input *X* can, after some number of applications of its adaptation algorithm, later come to improperly classify this same *X*. In a manner of speaking, "it forgot about *X* when it learned about pattern *Z*." An accommodation would, in contrast, be able to properly classify *Z* while retaining the ability to properly classify *X*.

Assimilation and accommodation are abilities closely conjoined. On the basis of his research, Piaget formulated the following two fundamental postulates:

> *First postulate:* Any scheme of assimilation tends to feed itself, that is, to incorporate outside elements compatible with its nature into itself. This postulate assigns a driving force to the process and therefore must assume activity on the part of the subject, but by itself it does not imply the construction of novelties; a rather large scheme (such as that of "existence") could assimilate the entire universe without being modified or enriching itself in compensation.
>
> *Second postulate:* The entire scheme of assimilation must alter as it accommodates to the elements it assimilates; that is, it modifies itself in relation to the particularities of events but does not lose its continuity (hence it can maintain closure and function as a cycle of interdependent processes) nor its earlier powers of assimilation. This second postulate (already proved valid on the biological level by the formation of phenotypical "accommodates") states the necessity for an equilibrium between the assimilation and the accommodation in order for the accommodation to succeed and remain compatible with the cycle [PIAG7: 7-8].

Here we see Piaget introducing the idea of a ***cycle*** into the discussion. The equilibrium produced by adaptation is a cyclic equilibrium. Piaget's research found that adaptation as a process in human development always involved the formation of closed cycles. A cycle is a sequence of activities that repeats after some time. Because of this repetition property, a cycle brings with it the possibility of *anticipation*, i.e., the ability to predict future outcomes once the subject has become cognizant of the observable features of the cycle. The formation of a cycle can be taken as the distinguishing mark of a system ***in equilibrium***, and in this sense the equilibration of assimilation and accommodation can be understood as the production of a stable cycle.

> The organism is a cycle of physiochemical and kinetic processes which, in constant relation to the environment, are engendered by each other. Let *a, b, c,* etc. be the elements of this organized totality and *x, y, z,* etc. [be] the corresponding elements of the surrounding environment. The scheme of organization is therefore the following:
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> (1) $a + x \rightarrow b;$
>
> (2) $b + y \rightarrow c;$
>
> (3) $c + z \rightarrow a$, etc.
>
> The processes (1), (2), etc. may consist either of chemical reactions . . . or of any physical transformations whatsoever, or finally, in particular, of sensorimotor behavior . . . The relationship which unites the organized elements *a, b, c,* etc. with the environmental elements *x, y, z,* etc.

> is therefore a relationship of *assimilation*, that is to say, the functioning of the organism does not destroy it but conserves the cycle of organization and coordinates the given data of the environment in such a way as to incorporate them in that cycle. Let us therefore suppose that, in the environment, a variation is produced which transforms x into x'. Either the organism does not adapt and the cycle ruptures, or else adaptation takes place, which means that the organized cycle has been modified by closing up on itself:
>
> (1) $a + x' \to b'$;
>
> (2) $b' + y \to c$;
>
> (3) $c + z \to a$.
>
> If we call this result of the pressures exerted by the environment *accommodation* (transformation of b into b'), we can accordingly say that *adaptation is an equilibrium between assimilation and accommodation*.
>
> This definition applies to intelligence as well. Intelligence is *assimilation* to the extent that it incorporates all the given data of experience within its framework. . . There can be no doubt either, that mental life is also *accommodation* to the environment. Assimilation can never be pure because by incorporating new elements into its earlier schemes the intelligence constantly modifies the latter in order to adjust them to new elements. Conversely, things are never known by themselves since this work of accommodation is only possible as a function of the inverse process of assimilation [PIAG8: 5-7].

The simple picture Piaget paints here is appropriate for the innate reflex schemes the infant is already equipped with at birth, but is a bit oversimplified when it comes to acquired schemes the infant constructs during the development of thought. For the innate reflex schemes, the picture above can be regarded as a succession of activities that close by, in a manner of speaking, *reverberation*, i.e. small disturbances are ignored and suppressed in the service of closing the cycle and establishing thereby a state of equilibrium. Piaget found that more complicated scheme structures develop through a cycle of interactions involving ***observables*** of two types. An observable in general is defined as "that which experience makes it possible to identify by an immediate reading of the given events themselves" [PIAG7: 43]. By "immediate reading" Piaget means sensuous perception.

Infants in the earlier stages of development do not distinguish between sensuous perceptions arising from their own actions and sensuous perceptions originating in the external senses (sight, hearing, touch, etc.). Thus, the construct $a + x$ in the notation above would correspond to a single observable, which Piaget denotes *Obs.OS*. This class of observable is characteristic of the levels of the earliest sensorimotor schemes. Later, by means we describe below, the child's on-going processes of assimilation and accommodation make it possible for him to distinguish between observables arising from his own activities, *Obs.S*, and those corresponding to external objects and events, *Obs.O*. The child brings his adaptation process into equilibrium through an interaction process of compensations, the simplest of which, illustrated in figure 13.1, is called a ***type I interaction***. The details of the elements of this interaction type are explained in the figure caption. What is key to our discussion here is that the interaction brings about a state of equilibrium by the

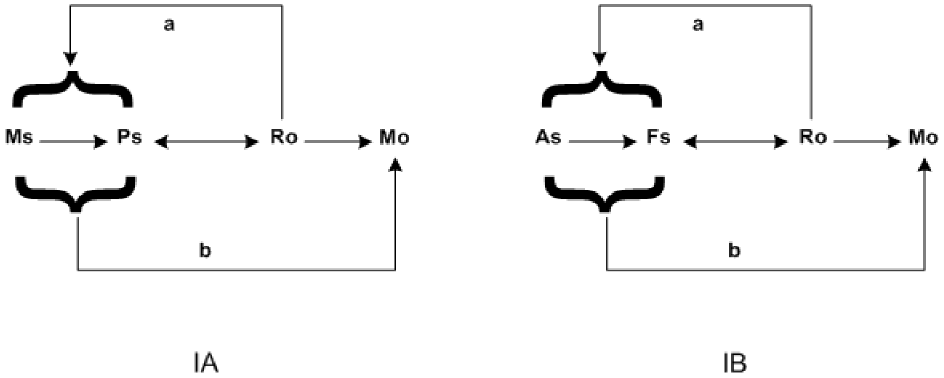

Figure 13.1: The type I interaction structure. Type IA is the structure describing physical sensorimotor actions made upon the object. The bracketed left-hand portion of the figure is the scheme observable *Obs.S* and the Ro and Mo terms are associated with the object observable *Obs.O*. Ms represents the child's movements and Ps ("thrust") represents feeling of exertion or effort involved in the scheme. Ro denotes the "resistance" of the object, i.e. that part of Obs.O constituting a disturbance resisting the equilibration of the adaptation cycle. Mo denotes the "movement" of the object, i.e. changes in Obs.O attributed to the reaction of the object to the actions made by the subject. Single-headed arrows denote dependencies, i.e. $x \rightarrow y$ means "*y* depends on *x*." Feedback path ***a*** denotes an "awareness" observable, i.e. the child's perception of resistance. Feedforward path ***b*** denotes an awareness of expectation, i.e. an anticipation of what the observable result Mo is to be. The arrows denote the direction of application of functions of these factors, while the double-headed arrow denotes the equilibration of Obs.S and Obs.O. Type IB is similar to type IA but the difference here is that Obs.S consists of mental rather than physical activities. As denotes the mental activity or operation (e.g. seriation, classification, etc.) and Fs denotes the application of the operation.

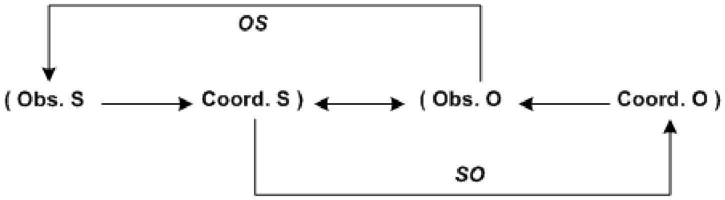

Figure 13.2: Type II interaction structure. The type II interaction is a higher equilibrium structure. New elements, Coord.S and Coord.O, are introduced in this interactions. These are called coordinations, and they are not observables but, rather, inferences drawn by the subject. Processes OS and SO take the place of the simple observables ***a*** and ***b*** of the type I interaction, and these processes themselves consist of interaction structures of type I. Single-headed arrows denote dependencies.

balancing of accommodations to the scheme and assimilation of the observations of *Obs.O*. The subject experiences a state of equilibrium when awareness of resistance, *a*(*Ro*), vanishes and the "movement" of *Obs.O* corresponds to the anticipation *b*(*Obs.S*). (In this sense, *a* and *b* can be regarded as cognitive functions). In equilibrium we are left with the simple cycle *Obs.S*↔*Obs.O*.

A new and higher form of equilibration becomes possible when the subject becomes capable of making *inferences of coordination* between his schemes and the objects to which these schemes are applied. This type of interaction is called a type II interaction structure and is illustrated in figure 13.2 above. An additional enhancement found in the type II structure is the formation of awareness and anticipation *processes* that take the place of the simple awareness and anticipation observables of the type I structure. Processes *OS* and *SO* are themselves comprised of

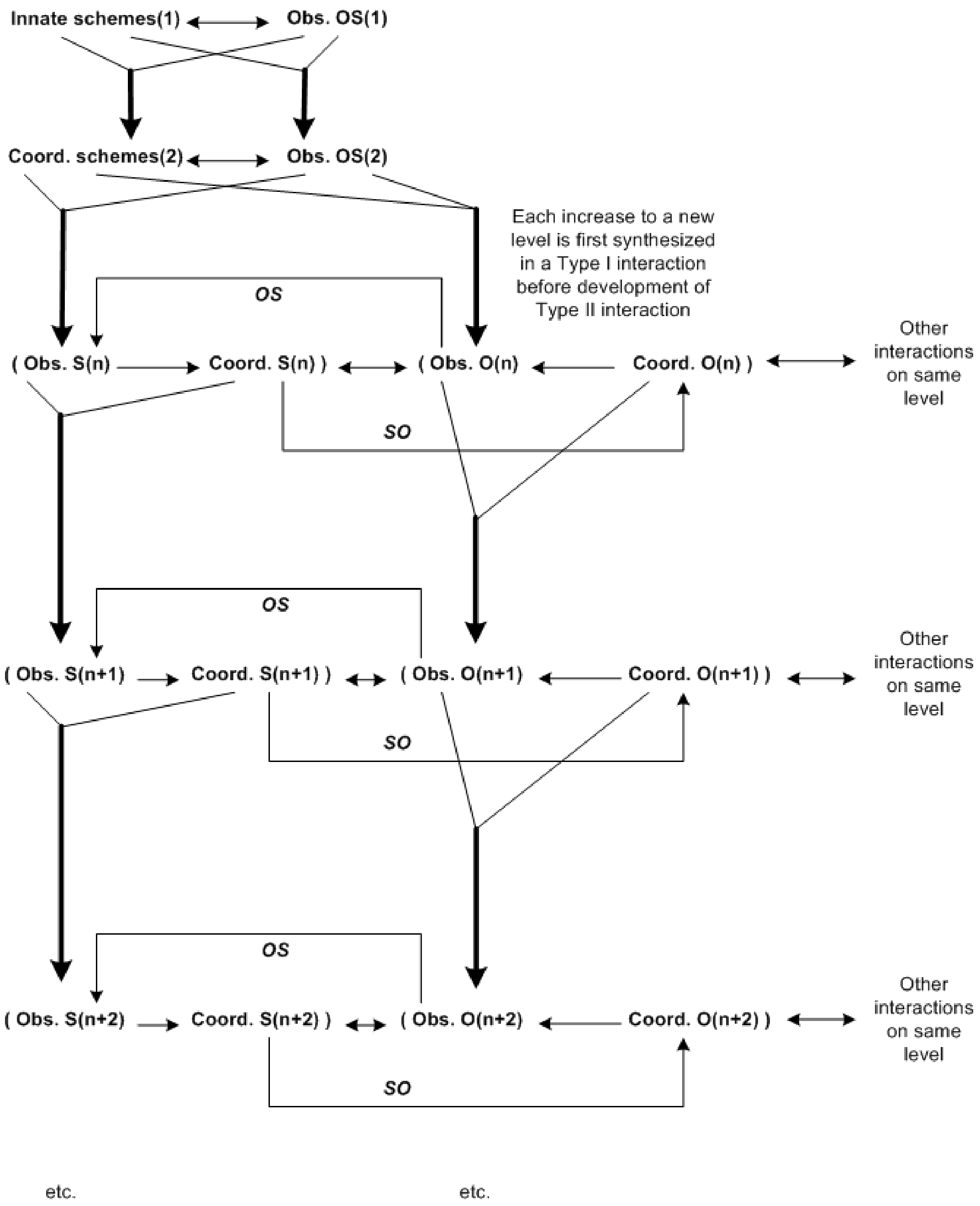

Figure 13.3: Piaget's hierarchy of increasing levels of equilibration.

type I interaction structures.

The full picture of Piaget's system of increasing levels of equilibration is illustrated in figure 13.3. Beginning from simple innate schemes and advancing, first through coordinations of simple schemes and later through equilibrated structures of type I and then type II, the subject actively builds upon his earlier constructs to an increasingly complex system of differentiated substructures within the totality of the overall scheme structure. These enhancements include the development of schemes for thinking as well as more refined schemes of physical activity. All this works through the unceasing balancing of the fundamental processes of assimilation and accommodation.

Refinements in the child's conception of observables *Obs.S* and *Obs.O* comes about through inferential coordinations of *Obs.S* and *Coord.S*, and *Obs.O* and *Coord.O* at the prior level of structure. Accommodation is at work in this process, so the new levels of *Obs.S* and *Obs.O* represent refinements in the structure of the child's conception of his schemes and the objects with which he is familiar. As figure 13.3 suggests, the same *fundamental process*, which Piaget called ***the central process of equilibration***, is at work throughout all stages of intellectual development.

The Piagetian model just presented obviously leaves a number of questions of detail unanswered. One could wish Piaget had expressed his ideas more clearly in [PIAG7], but he did not. Rather, he leaves it to the student of his work to sift through the many experimental results that preceded the development of this model, and, in that way, develop a grasp of the large ideas he presents in the form of the figures shown above. Unlike most of his many books, *The Development of Thought* is a "theory" book providing no detailed examples within its covers. It is not the purpose of this text to teach Piaget's theory of development. Rather, the purpose in introducing it here is to provide a summary overview of the "big picture" of cognitive development theory as a backdrop for our discussion of adaptation in network system models. With that in mind, let us proceed to an examination of the relevance of Piaget's major ideas in the context of neuropsychological system modeling and the partitioning problem.

§ 2. The Partitioning Problem in a Network Systems Context

The obvious first question we should deal with is whether or not the psychological findings we have just reviewed are capable of interpretation in the contexts of network systems and neurology. The major psychological ideas coming out of Piaget's theory are: (1) Adaptation as a process takes the form of ***cyclic structures*** and comes to a successful state of equilibrium when this cyclic structure succeeds in closing on itself with the suppression of continued innovations from one period of the cycle to the next; (2) If success in (1) is not achieved, the cycle ***ruptures***, which cognitively corresponds to the subject "losing interest" and abandoning the attempt; (3) Accommodation actions during adaptation are always such that the totality of the overall structure is conserved, which means that substructures constructed by accommodation processes are merely differentiations within the larger scheme structure; (4) The successful accomplishment of (3) means that any unique and new transformations engendered by the central process of equilibration can be distinct from those of other substructures, but in all cases the total structure loses none of its previous capacity for assimilation; (5) Scheme structures can assimilate to each other (***reciprocal assimilation***), leading to the coordination of different schemes and the production of a higher and better overall structural ***organization***; (6) The accomplishment of (5) calls for some schemes to become "mobile" – i.e. to become applicable to new situations the system could not previously deal with; (7) affective perceptions play a regulating role in the central process of equilibration, acting as "energetics" for adaptation activities and "terminating regulations" for bringing these activities to a close; (8) intelligence and objective cognition begins as a "blank slate" (no innate ideas, no copy-of-reality mechanism, no pre-wired concepts[3]) and is constructed through meaning implications taking their fundamental context from the subject's own activities and constituting a form of a proto-logic of actions leading to the construction of a logic of meanings. Let us compare neural network theory with these facets of psychology.

§ 2.1 Adaptation as Cyclic Structure

It is not common in neural network theory to speak of adaptation in terms of cycles or cyclic structure. Nonetheless, the idea of a cyclic structure in the process of adaptation is inherent in most of the major network adaptation algorithms that have been published. The earliest and simplest example is the Madaline rule algorithm illustrated in figure 13.4 [WIDR2]. The individual Adaline nodes in the network are adapted, when they are commanded to by the control algorithm (known as the "job assigner" function), using the α-LMS algorithm. (The version published in 1962 used the μ-LMS algorithm).

Different variations on the basic method shown in figure 13.4 have been developed [WIDR3]. Here we will describe the simplest version. When presented with an input vector X, the network produces an output vector Z. Z is compared against a desired response vector, D, to produce some error metric (usually mean-squared error). The job assigner block then applies a small perturbation Δs to the first node in the first layer to produce a perturbation in that node's excitation variable, $s_n \rightarrow s_n \pm \Delta s_n$. This produces a perturbed output that feeds forward through the

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[3] In the 1980s some of Piaget's principal findings came under attack by younger investigators who claimed to find evidence that pre-wired concepts and foundational knowledge of "external reality" exists in infants. Critics of this theory accuse these investigators of jumping to their conclusions without an adequate demonstration of fact, and thus has arisen controversy in developmental theory. Some very recent findings from independent laboratories have tended to refute the claims of the new developmentalists and favor the original findings of Piaget et al. So that you know where he stands, your author does not agree with the so-called refutations of the Piagetian theory and does agree with the major pillars of Piaget's system. This is not from a bias toward one view or the other but from the weight of all the evidence and the breadth of explanation provided by the Piagetian theory in comparison to the fragmented and ad hoc character of the opposing hypotheses.

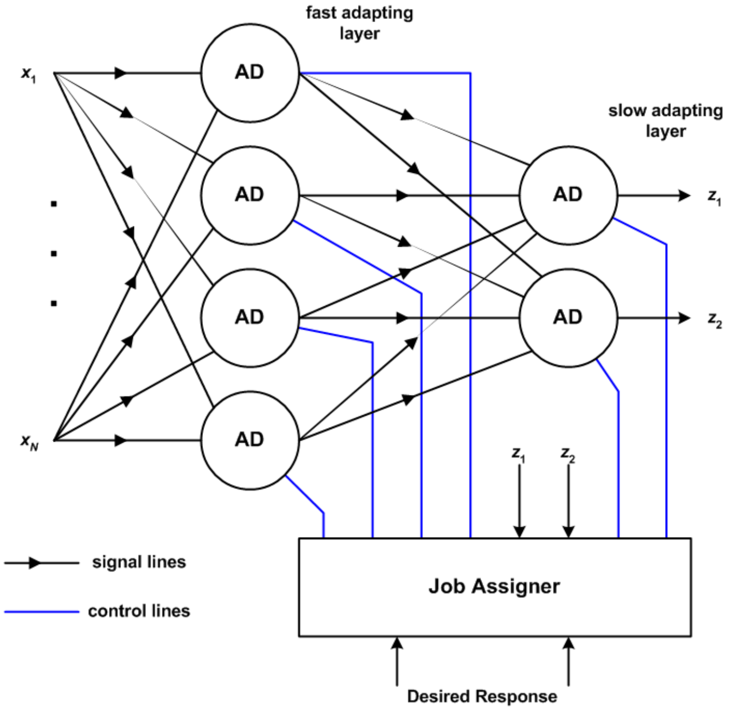

Figure 13.4: Madaline network example. AD = Adaline node. The network is presented with input vectors X and produces output vectors Z. Z is compared against a desired response at the "job assigner," which is the network adaptation control algorithm. The job assigner perturbs the AD nodes one at a time by injecting an additive signal that changes the node's excitation s_n. If this results in a better match between Z and the desired response, the Adaline adapts by means of the α-LMS algorithm using its own perturbed output signal as the local desired response. Different specific variations of the job assigner algorithm have been used. The simplest version begins with a small perturbation, and if no perturbed AD results in any improvement, the perturbation is gradually increased until at least one node is chosen for adaptation.

network. If either perturbation ($\pm\Delta s_n$) produces an improvement in the error metric, the perturbation is removed and the Adaline node is adapted using its perturbed output as the desired response. If no improvement results, the Adaline is not commanded to adapt and the job assigner moves on to the next node. The process continues until the job assigner has tested all the nodes in the network. If no Adaline undergoes adaptation, the perturbation is increased by a small amount and the procedure is repeated.

More sophisticated version of this algorithm exist. One of them, known as the Madaline III rule [WIDR3], is mathematically equivalent to a more widely known algorithm called the ***back-propagation algorithm*** [WERB].[4] Indeed, the backpropagation algorithm can be regarded as equivalent to distributing the function of the job assigner block throughout the network rather than centralizing this function within one functional block as shown in the figure above.

The cyclic character of this algorithm is evident in the actions of the job assigner function. The

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[4] As an historical footnote, the Madaline III rule was not discovered until long after the backpropagation algorithm. In some ways, Madaline III can be regarded as simply a different way to implement the back-propagation algorithm.

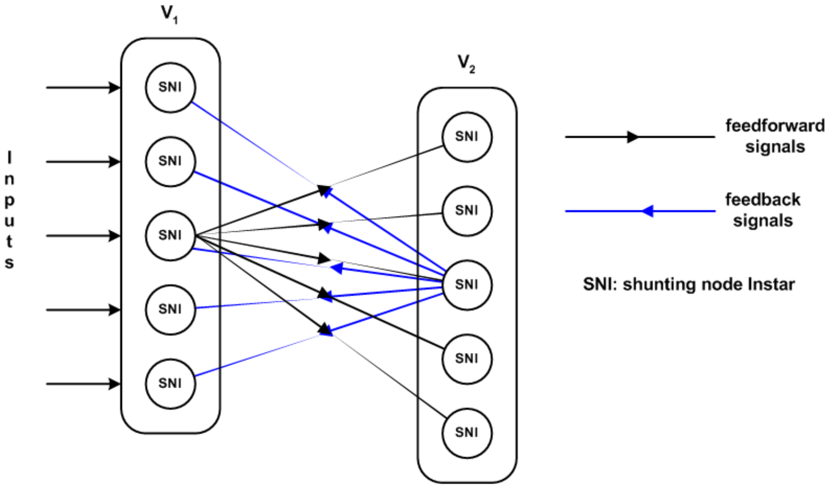

Figure 13.5: Minimal ART network for pattern classification. The diagram is simplified to show only one feedforward pathway from layer V_1 to layer V_2 and one feedback pathway from V_2 to V_1. Each layer is a competitive layer but differs from the MAXNET discussed in chapter 12 in that the nodes in the ART network are shunting node Instars and the feedback pathway employs another type of node model called an *Outstar*.

simpler versions of Madaline rules will make only a single pass through the network, although some versions may dwell on the given input signal X and carry out multiple adaptation passes until no further improvement is made. Which approach is better is a question still under debate since the answer seems to be application-dependent.

As noted in chapter 12, the Madaline network does require a desired response signal to be compared against Z. This is not a particularly serious difficulty for engineering applications of artificial neural networks, but it does raise serious issues in terms of the suitability of this model for psychophysical network system modeling in computational neuroscience. The objections raised in this regard might possibly be answered by use of an actor-critic structure, although this would entail some significant modifications to the comparison function within the job assigner block. A more serious issue, however, is the fact that this network is a feedforward network, whereas the neurological organization of the brain has the form of recurrent networks. No widely successful, efficient method has yet appeared that extends the basic idea of the Madaline rule approach to recurrent networks.

A second example, much better attuned to biological signal processing, is represented in figure 13.5 [GROS6]. This network is called an ART (adaptive resonance theory) network. The details of how this network model works are not so easy to explain as the Madaline rule, and we will postpone a detailed discussion until later, after we have had a chance to discuss properties of competitive networks in chapter 14. However, its workings can be explained qualitatively without much difficulty.

> This unit can establish an *adaptive resonance*, or reverberation, between the two regions [V_1 and

> V_2] if their coded patterns match, and can suppress reverberation if their patterns do not match. This concept yields a model of olfactory coding within the olfactory bulb and the prepyriform cortex. The resonance idea also includes the establishment of reverberation between conditioned reinforcers [V_1 to V_2 signals] and generators of contingent negative variation [V_2 to V_1 signals] if presently available sensory cues are compatible with the network's drive requirements at that time; and a search and lock mechanism whereby the disparity between two patterns can be minimized and the minimal disparity images locked into position. Stabilizing the code uses attentional mechanisms, in particular nonspecific arousal as a tuning and search device [GROS6].

Accomplishing these capabilities requires a different class of Instar from the one we have been using, namely the class of Instar models here called **shunting node Instars** (SNIs). It also requires a new type of map model we have not yet discussed, known as an ***Outstar*** node. We will explain these models later when we discuss adaptive resonance theory. The layers V_1 and V_2 each have reciprocal connections among their SNIs and form competitive layers. These are superficially similar to the MAXNET network discussed in chapter 12, but an ART competitive layer is a more sophisticated structure than a simple MAXNET and would not be called a "winner take all" network in the usual sense of that terminology. A simple WTA network is non-adaptive and merely adjudicates a "winner." An ART competitive layer does much more than this.

More germane to our present discussion is this idea of "reverberation" in the ART structure. When an input vector X_1 is applied to V_1, the combination of inhibitory lateral connections within each layer and the feedback from V_2 to V_1 result in a complex pattern of signal changes in both V_1 and V_2. Eventually V_2 will settle into a stable activity pattern and the feedforward signal from V_1 to V_2 stabilizes in such a way as to maintain the pattern at V_2. This is the *resonance condition* in response to X_1. Unlike Piaget's cycles, which constitute a continually-varying-in-time response mathematicians would call a ***limit cycle***, the equilibrium condition in the ART network is a fixed-point response. However, three things are noteworthy in this regard. First, Piaget's theory is large scale, i.e. it is described at the scale of the organism (specifically, the person), whereas a single ART network such as in figure 13.5 is "small scale." Second, the signal variables in the network system model are "activities"; they correspond to very dynamical neuronal firing patterns. Third, we have not said where X_1 comes from nor what generates it. If all or part of it comes from downstream ART networks (retrograde feedback within the larger system), we can reasonably expect that feedforward output projections from V_2 will have a rippling effect through the system that may eventually result in a new input vector X_2 being presented to V_1.

When the input is changed to some X_2, the V_1 to V_2 signal is *suppressed* due to the feedback from V_2 to V_1. This is because the V_2-to-V_1 feedback signal in an ART network is a coded representation of X_1 that the network has "learned" through the process of adapting its weights. So long as X_1 remains fixed, this feedback response maintains the V_1-to-V_2 excitation of V_2, but this maintenance is disrupted when X_1 changes to X_2. In order to accomplish this, network layer V_2 is equipped with what Grossberg terms a ***quenching threshold***. What this means is that the V_1-to-V_2 signal has to exceed a certain level of activity in order for reverberations in V_2 to set up the resonance condition. Otherwise, the activity in V_2 is inhibited and the V_2-to-V_1 feedback is removed. Thus, if X_2 is *sufficiently different* from X_1, the "reverberation cycle" in the network is *ruptured*, X_2 establishes a new V_1 signal, and V_2 responds by producing a new activity pattern, namely one that "encodes" for X_2. This is how the ART network "knows" a significant change has occurred at the input X.

§ 2.2 Assimilation and Accommodation

Naturally, the foregoing is merely a description and is not sufficient in detail to describe how an ART network accomplishes all this. That explanation will come later. But some things that are important to appreciate about an ART network are the following. First, the network does operate cyclically; static abstract activity levels in a map model do *not* correspond to static neuronal states but to dynamical ones. Second, the network will ignore *small* differences between X_1 and X_2; this is assimilation. Third, the method by which adaptation of the weights occurs in the network "protects" previously "learned" weight settings from being disturbed by every input vector X that comes along. As Grossberg describes it,

> Properly defining signal and noise in a self-organizing system raises a number of subtle issues. Pattern context must enter the definition so that input features which are treated as irrelevant noise when they are embedded in a given input pattern may be treated as informative signals when they are embedded in a different input pattern. The system's unique learning history must also enter the definition so that portions of an input pattern which are treated as noise when they perturb a system at one stage of its self-organization may be treated as signals when the perturb the same system at a different stage of its self-organization. The present systems automatically self-scale their computational units to embody context- and learning-dependent definitions of signal and noise [GROS10].

An assimilation process is *integrative*. It ignores differences (treats them as irrelevant noise). An accommodation process is *differentiating*. It responds to differences by producing sub-structures that deal with the differences without injury to previous successful assimilations. An ART network accomplishes both these things, and it does so automatically. *How* it accomplishes it takes a fair amount of explaining, but if ART were obvious, Grossberg would not be famous. The main point is that ART networks not only succeed in exhibiting behaviors that come out in good agreement with neurological data (such as is obtained by PET or fMRI scans), but do so in a manner on the *small scale* that is, so far as we have looked to this point, functionally consistent with what is observed on the *large* scale in the psychological findings of developmental psychology.

Of course, this may be coincidence, or it may be "something in the nature of adaptation itself" that accounts for this unlooked-for similarity. At present we cannot rule out the first. But as for the second, there are unsupervised adaptation algorithms that do *not* succeed in successfully preserving the overall structural integrity of the system as they accommodate themselves to input data. This ***failure in conservation*** is the chief symptom of the stability-plasticity dilemma in those systems that tend to favor plasticity over stability.

> Analysis of the competitive learning model revealed a fundamental problem which is shared by most other learning models that are now being developed and which was overcome by the adaptive resonance theory. . . This instability problem was too fundamental to be ignored. In addition to showing that learning could become unstable in response to a complex input environment, the analysis also showed that learning could all too easily become unstable due to simple changes in an input environment. Changes in the probabilities of inputs, or in the deterministic sequencing of inputs, could readily wash away prior learning.
>
> The instability of the competitive learning model thus emphasized the fundamental nature of the *stability-plasticity dilemma* . . . How can a learning system be designed to remain plastic in response to significant new events, yet also remain stable in response to irrelevant events? How does the system know how to switch between its stable and its plastic modes in order to prevent the relentless degradation of its learned codes by the "blooming buzzing confusion" of irrelevant experience? How can it do so without a teacher?
>
> Rumelhart and Zipser (1985) were able to ignore this fundamental issue by considering simple input environments whose probabilistic rules do not change through time. Other modelers, for example Kohonen (1984), have stabilized learning in their applications of the competitive learning model by externally shutting off plasticity before the learned code can be erased. This approach creates the danger of shutting off plasticity too soon, in which case important information is not learned, or too late, in which case important learned information can be erased. The only way to overcome instability using this approach in an unpredictable input environment is to assume that the observer, or teacher, who shuts off plasticity is omniscient. . .
>
> Yet other modelers, such as Ackley, Hinton, and Sejnowski (1985), Hopfield (1982), Knapp and Anderson (1984), McClelland and Rumelhart (1985), Rumelhart, Hinton, and Williams (1986), and Sejnowski and Rosenberg (1986), have stabilized their models by externally restricting the input environment. They thereby recast the problem of model instability into one about model capacity: What sorts of restricted input environments can these models handle before their learned codes are washed away by the flux of input experience? None of these learning models has yet addressed the general instability problem that was articulated a decade ago [GROS10].

In developmental psychology terms, an adaptation is an equilibrium between assimilation and accommodation. ART networks accomplish this, and do so within the requirements that must be met to satisfy the Piagetian definition of structure. Is ART-based adaptation the only way this can be accomplished? At present it is the only biologically *and* psychologically consistent method known for doing this – or, at least, the only one widely known as such by the general community of neural network theorists. It is not the only adaptation method that incorporates new information without the danger of losing old information.

A interesting learning system (not a neural network system model) was developed several years ago by Brennan [BREN]. This particular system has nothing in common with biological signal processing or with computational neuroscience, although it was to some degree inspired by Grossberg's work. Rather, this system was designed to adaptively learn and implement Boolean logic functions. It was based on a special-purpose computing device called a content-addressable parallel processor (CAPP) and used an interesting cyclic adaptation algorithm called the ALM (adaptive logic minimization) algorithm. Its internal content-addressable memory used, in effect, a novel kind of multi-level (non-binary) representation based on a so-called "tidbit" (ternary information data bit) that could represent "0", "1", or "don't care." It also included a memory mechanism by which the machine could declare a tidbit to be "frozen" (i.e., unalterable) in the "0" or the "1" state. "Learning" stability was achieved, without sacrificing plasticity, by the simple expedient of freezing the tidbit when a learning instability was encountered. In effect, the machine addressed the stability-plasticity dilemma by "remembering" the past adaptation history of each tidbit. Now, this "learning" machine has nothing in common with biological neural networks beyond the fact that digital logic circuits are McCulloch-Pitts "neurons." But it does serve to demonstrate that, from a strictly mathematical-algorithmic point of view, there is more than one way to skin a cat. Perhaps there may be others that could more reasonably represent neurological systems. Be that as it may, any psychophysical model of neural network systems *must* successfully address the stability-plasticity dilemma and do so in a way that meets Piagetian structure requirements if it is to claim both biological *and* psychological significance.

§ 2.3 Schemes and Structuring

The innate sensorimotor schemes the infant builds upon in the development of intelligence are initially uncoordinated. In a manner of speaking, the infant does not begin life with one system of sensorimotor intelligence but, rather, with many. Gradually and over time, the different types of sensorimotor schemes integrate with one another to form structures – or, as Piaget puts it, the separate schemes are coordinated. The way in which this happens is through the development of what Piaget calls ***mobile schemes***. These arise initially from simple reciprocal assimilations between pairs of schemes. These reciprocal assimilations and the mobile schemes that eventually develop from them are central to the process of structuring the higher and better levels of equilibration illustrated in figure 13.3.

Now, the first question one can and should reasonably ask is: What, if anything, in a network system model corresponds to a Piagetian scheme? A scheme is what can be repeated and generalized in an action, and so under this general definition the network adaptation algorithms we have described are schemes in the sense that the algorithm is applied to adaptation of every subnetwork in the overall network. Yet it is also obvious this is not at all the same sort of thing as what Piaget et al. studied. The presence of Piagetian schemes are revealed by behaviors of the subject, and neurological network adaptation is not a behavior observable by the psychologist.

The question of how – and even of *if* – a scheme can be viewed from a neural network system perspective is but one concrete example of a wider issue that always confronts interdisciplinary researches. There have been three distinguishable approaches taken by researchers, which may be and have been term "atomism", "holism", and "structuralism."

> The method intended to master the problem of wholes – which at first seems to be the most rational and rewarding because it corresponds to the most elementary intellectual operations (those of assembling or adding together) – consists in explaining the complex by the simple, in other words in reducing phenomena to atomistic elements, the sum of the properties of which is supposed to represent the whole which has to be interpreted. Such atomistic methods of posing problems eventually lead to the laws of structure as such being forgotten or distorted. . .
>
> The second trend which can be observed in a number of separate disciplines is one which, in the face of complex systems, consists in stressing the characteristic of 'wholeness' peculiar to these systems, while considering that wholeness to be directly 'emergent' from the assembly of elements and as imposing itself upon them, by structuring them, as a result of this constraint of the 'whole'; above all, it consists in considering the whole to be self-explanatory by the mere fact of its description. Two examples of such an attitude may be given . . . The first example is that of Gestalt psychology . . . The prevalent opinion today is that this method offers good descriptions but not explanations . . . In an entirely different field, Durkheim's sociology proceeded in a similar manner by seeing in the social whole a new totality emerging on a higher scale from the assembly of individuals and reacting upon them by imposing on them a variety of 'constraints'. It is interesting to note that this school . . . likewise died a natural death for the lack of a relational structuralism which might have supplied some laws of composition or construction instead of referring unremittingly to a totality conceived as ready-made.
>
> The third position, then, is that of structuralism, but interpreted as relational, that is to say as positing systems of interactions or transformations as the primary reality and hence subordinating elements from the outset to the relations surrounding them and, reciprocally, conceiving the whole as the product of the composition of these formative interactions. It is of great interest . . . to note that this trend . . . is still more general and manifests itself just as clearly in mathematics and biology. . . Thus structuralist research gives rise to at least three major inter-disciplinary problems[:] *a.* A problem of comparison of structures according to their spheres of application. . . *b*. Whereas the explanation of wholes by atomistic methods leads to a geneticism without structures and the theory of emergent wholes leads to a structuralism without genesis . . . the central problem of structuralism in the biological and human sciences is that of reconciling structure and genesis, since every structure involves a genesis and every genesis must be conceived as the (strictly formative) transition of an initial structure to a final structure. . . *c.* The third major problem which arises in comparative studies is that of the nature of the structures arrived at, i.e. whether they constitute simple 'models' in the service of theoreticians or whether they should be considered as inherent to the reality under study, in other words as structures of the subject or subjects themselves. This question is fundamental [PIAG1: 21-25].

Earlier in this book we saw Grossberg refer to the same issue in different words when he wrote,

> In summary, the relationship between the emergent functional properties that govern behavioral success and the mechanisms that generate these properties is far from obvious. A single network module may generate qualitatively different functional properties when its parameters are changed. Conversely, two mechanisms which are mechanistically different may generate formally homologous functional properties. The intellectual difficulties caused by these

> possibilities are only compounded by the fact that we are designed by evolution to be serenely ignorant of our own mechanistic substrates. . . Thus we cannot turn to our daily intuitions or to our lay language for secure guidance in discovering or analyzing network models [GROS10].

Physics – that most specialized and 'atomistic' of disciplines – rarely has to face any issues such as these; neuroscience, in contrast, cannot avoid facing them. This brings us to the point where a clear distinction between the roles of *function* and *structure* is essential for research.

> In all the sciences of life and of man there has always been opposition between so-called functionalist trends and structuralist trends. . . We must first ask ourselves whether the conflicts between functionalism and structuralism do not in part stem from too narrow a conception of structures which emphasizes only their characteristics of totality and internal transformations but overlooks their essential property of self-adjustment. For if this property is neglected, the structure takes on a static aspect which devalorizes functioning, thus giving the impression that with structure one has established a kind of permanent 'entity' related to the unchangeable properties of the human spirit or of society in general. Hence the skepticism of functionalists vis-à-vis such a hypothesis, which can in effect lead to anti-functionalism.
>
> But if one distinguishes between formal or formalized structures, whose adjustment is due to the axioms conferred upon them by theoreticians, and real structures which exist independently from theory, it is necessary to ask how structures are conserved and how they act, which comes down to raising the question of their functioning. Their self-adjustment can in some cases be assured by rules or norms . . . but then these rules already represent a function, that of maintaining the integrity of the structure by a system of constraints or obligations. On the other hand, it may be that the structure is not completed; in its formative stages its self-adjustment will of course as yet imply not a system of rules but a self-regulation whose functioning may involve multiple variants. In particular, it may happen that a structure is not capable of 'closure' but depends on continual exchanges with the exterior . . . It is in such situations that functions are distinct from structures and that functionalist analysis becomes necessary to such a point that its partisans sometimes forget that it is difficult to conceive of functions without organs or overall structure. . .
>
> Generally speaking one may . . . consider functioning as the structuring activity whose structure constitutes the result or the organized event. In the case of a completed structure functioning is identical with those transformations which are real among all those which are possible, and which characterize systems as such. As to function, the term can be used to designate the particular role played by a specific transformation relative to the entire set of transformations (the two meanings, biological and mathematical, of the word 'function' then tend to become interchangeable). But in the case of a structure in the process of formation or development, or generally not 'closed', where for that reason self-adjustment so far consists only in regulations and where exchanges are open to the exterior, functioning is formative and not merely transformative and functions correspond to utilities (or values) of various kinds depending on the roles of conservation, reinforcement or perturbation which the functioning of sub-systems may play in relation to the total system, or vice versa [PIAG1: 35-37].

Self-regulating self-adjustment – i.e., adaptation – is thus seen as an underlying capacity for the *development* of psychological functions and, by proxy, neurological functions corresponding to them in the central nervous system. It is in this context that viewing neural network adaptation as a "learning" process is too narrow. Equilibration – the process of adaptation in bringing the twin requirements of assimilation and accommodation into balance – is broader in scope than this and "learning" is merely one of its many outcomes. One can detect the shadow of this in theories of artificial "cognitive systems" and so-called "knowledge representation" research. One example

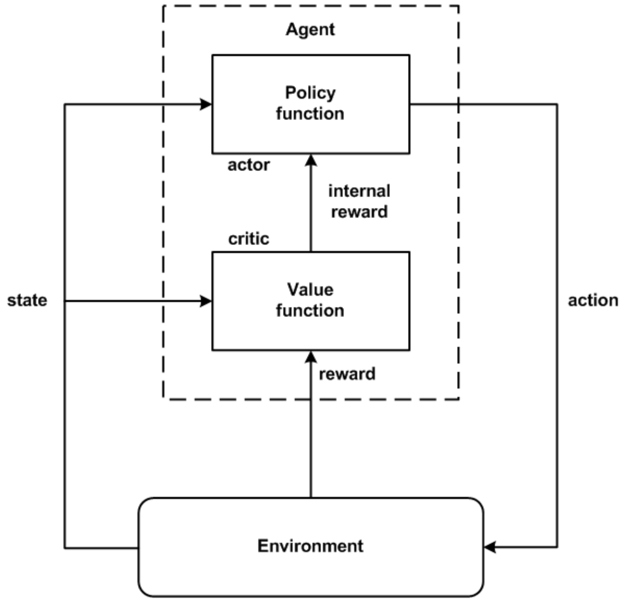

Figure 13.6: The generic actor-critic model.

of this is provided by the generic actor-critic model. Figure 13.6 illustrates the generic actor-critic model [BART1]. The "agent" corresponds to the whole behaving organism and includes as a part of this system the entirety of all its interacting network systems (i.e. its central nervous system). Within its CNS network system functions are split into two general classes. The "policy function" represents all the network systems related to the *observable* aspects of its cognitive, affective, and sensorimotor functions. The "value function" represents those generally *unobservable* aspects of psychological function associated with emotions, motivations, drive states, etc.

The environment is acted upon by the agent through the agent's externalized actions. In turn, the environment is said to act upon the agent in two ways. First, the environment is said to affect the agent through inputs regarded as producing a "sense" of reward or punishment. Pain is the most obvious specific example of this, but the "reward" input is held to be more general than this, which is one reason it is often described very vaguely in many papers. The "reward/punishment" *signaling* is further divided into two aspects. There is an "external" aspect that is supposed to correspond to direct effects due to the environment and registered by the agent's sensory capabilities. There is also an "internal" aspect corresponding to the agent's psychophysical *reactions* to the affective stimulus.

Second, the environment is said to affect the agent through an environmental "state." This, too, is a frequently equivocal term because it does not mean the "state of the environment" but, rather, what we might call the "situation" in which the agent "finds itself operating in." State used in this context does not refer to the state variables of the environment model, but to signal data by

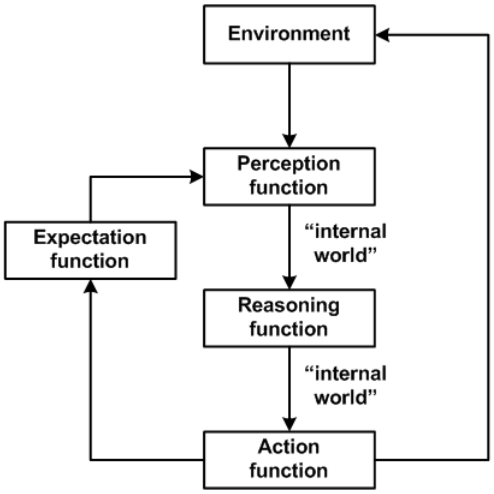

Figure 13.7: Agent reasoning loop model.

means of which the agent can act as an ***observer*** of the environment. Thus, implicit in this model is the presence of what system theorists call an ***observer function***. Common examples of this found in the wider systems literature include the Luenberger observer [CHEN] and the Kalman filter observer [GELB]. Although it is common to hear this function described as the agent's "world model," from a psychological point of view this description is not quite correct. What is more correct is to say the observer function is a subsystem, within the overall structure of the agent, having the function of *building* a "world model."

It is perhaps clear from what has just been said that the model of figure 13.6 by itself is not complete enough to adequately describe the overall set of ideas in play here. One might say figure 13.6 is a "physiological" model (in a loose sense of that term) representing the physical component of an "intelligent system." Along with this "physiological" model, the ideas we are discussing require a "psychological" model to cover the "mental" dimension of the mind-brain system implied by the language of the actor-critic model. Such models are a constant concern of "knowledge representation" theory and "artificial intelligence" theory in its different guises. One such model is illustrated in figure 13.7 [WOOD]. The common point between this model and the previous one is the "environment" block. Otherwise, the blocks in this diagram carry psychological connotations (perception, reasoning, expectation), and this extends to the "decision making" aspect of its "action function." The "internal world" depicted in this figure can justly be called the "subject's world model."

Relational structuralism as described above by Piaget requires the conjoint consideration of these two dimensions of modeling. That this is so is expressly demonstrated by the methods of psychophysics, where psychological phenomena are *correlated with* brain activity. Thus, the perception function of figure 13.7 is not concerned with signals per se but, rather, with the

context of signals in relationship to the functions through which behaviors can be ***expressed*** in physical actions and stimuli can be ***assimilated*** in the network systems. The reasoning function of figure 13.7 has not so much to do with logic or judgment as it does with the initiation or termination of ***signaling schemes*** that act on various subsystems within the overall agent. The action function of figure 13.7 has not so much to do with control of specific actions as it does with the determination of psychological ends and expressive means that give the physical action in figure 13.6 a ***subjective context*** for the expressed behavior. Finally, the expectation function of figure 13.7 has not so much to do with cognitive appraisal (although this is part of it) as it does with establishing ***anticipations by which 'success' or 'failure' of the behaviorally expressed scheme*** are to be evaluated.

The equilibration process is the process by which the system is brought to an equilibrium state as *structure implicates functioning and functioning produces structural transformation*. If we use figures 13.6 and 13.7 as example models, the necessary condition for this is the conjoint equilibrium of both these "dimensions" of ***intelligence structure***. Seen in this general context, a ***scheme*** has two dimensions as well. In its *interior* dimension a scheme is a general ***regulation*** for effecting transformations. In its *exterior* dimension a scheme is *exhibited* by the observable sequence of transformations within the system it effects.

§ 2.4 The Formation and Modeling of Scheme Structures

In his studies of the psychology of functions [PIAG5] and the development of thought [PIAG7], Piaget et al. were able to identify four elementary ***coordinator functions*** and three basic ***compensation regulations*** that turned up universally at all levels of development. The four elementary coordinator functions are: (1) ***the association coordinator***, which produces ordered pairs of objects or actions (e.g. the pairing of one network subsystem with another to produce an effect); (2) ***the repetition coordinator***, which serves reproductive assimilation and, as the name implies, is exhibited by simply repeating an action (Piaget elsewhere calls this effect a "circular reaction"); (3) ***the identification coordinator***, which serves recognitory assimilation, as in the formation of basic classifications; and (4) ***the permutation coordinator***, where one thing is substituted for another in the execution of the action of a scheme [PIAG5: 172-173].

The three fundamental compensation behaviors are: (1) ***type-α compensation***, which assimilates by *ignoring* or *canceling* a disturbance; (2) ***type-β compensation***, which transforms disturbances into variations by forming reciprocal relationships; and (3) ***type-γ compensation***, which in a sense is the synthesis of the first two; it *anticipates* possible variations and *transforms* disturbances in reciprocal relations into mere variations, which thereby permits variations to be cancelled and leads to the construction of *reversible* schemes. Type-α compensation is a form of classification; type-β is a form of seriation (ordering structure); type-γ combines classification and order structuring to produce inverse transformations for transformations already discovered by previous type-β compensations.

Piaget called assimilation "the formatory mechanism of schemes." The coordinator functions and compensation behaviors just described are the basic mechanisms for building assimilation capabilities through the equilibration process. From this perspective, we can say *wherever we find the coordinator functions and compensation behaviors in action, there is where we are witnessing the telltale mark of scheme formation in action.* Naturally, for this guideline to have substance, we must consider the system in both dimensions discussed above.

The actor-critic model and Woods' reasoning loop model (figures 13.6 and 13.7) originate from mathematical theories of artificial neural networks and artificial intelligence. If these models are to represent not merely artificial systems but actual biological systems, they must be tied to the dynamics of intelligence depicted in the interaction structures of figures 13.1 to 13.3. We begin by looking at the formation through interactions of elementary coordinated action schemes.

Figure 13.8 depicts the sequence Piaget found to underlie these formations. To provide a specific example, two innate schemes an infant exhibits on the first day of life are the sucking reflex (if anything contacts the baby's lips, he will suck it) and non-specific arm movement schemes. If by accident an arm movement happens to bring the baby's fingers into contact with the lips, he will suck his fingers, but for a few weeks the baby does not know how to deliberately bring his fingers to his mouth. (Indeed, at this stage the baby does not know he has fingers, arms, or a mouth; these object-concepts have not yet been formed). Over time, he will discover through

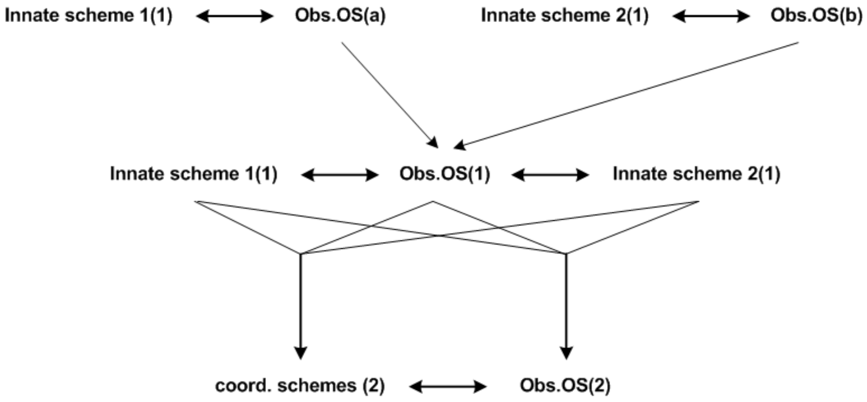

Figure 13.8: Formation of early coordinated schemes. The observable Obs.OS(1) is the point of intersection for two initially uncoordinated sensorimotor schemes. Although the sensory information perceived will have differences between the two interactions initially, type-α compensation allows these differences to be ignored when two motor schemes act simultaneously on the same object. This compensation is what allows the two action schemes to eventually be coordinated with one another by type-β compensations.

a process of groping how to bring the fingers to his mouth so that he can suck them [PIAG8]. But before this happens, common sensational elements arising from his actions must come together to constitute an Obs.OS(1) as the point of intersection between the arm movement scheme and the sucking reflex scheme. Two things in particular must be noted here. First, Obs.OS(1) is discovered by accident; the infant has no cognitive "expectation" prior to the experience. Thus the expectation function in figure 13.7 is not initially in place but, rather, forms as a consequence of the baby's groping movements. The *construction* of Obs.OS(1) relies upon the association coordinator, the repetition coordinator, and type-α compensations. Second, owing to the absence of a priori expectation in advance of experience and the necessity for an expectation function to be formed, we can see that Woods' model is incomplete. There must be, in addition to the factors shown in figure 13.7, an "evaluation function" serving as the ground for the formation of the expectation function. Furthermore, it is psychologically incorrect to suppose a motor action feeds directly to an "expectation" function because we are not cognizant of motor commands themselves but only of the effects body motion has on perception. Finally, it is impermissible to speak of "reasoning" prior to the formation of object concepts since reasoning is directed at objects. Rather, it would be better to call this a "judgment" function, the word judgment meaning **the act of subsuming particular representations under general ones**. These modifications to Woods' model are illustrated in figure 13.9.

Prior to the formation of object concepts, it is incorrect to regard the evaluation function as some form of cognitive appraisal. Rather, the fundamental nature of an evaluation function must be subjective: evaluation in regard to the subject's subjective state. Thus, the putative evaluation function depicted in figure 13.9 would belong to the "critic" block of figure 13.6 rather than to the "policy" block. The minimal general classes of evaluations are then described as satisfactions or

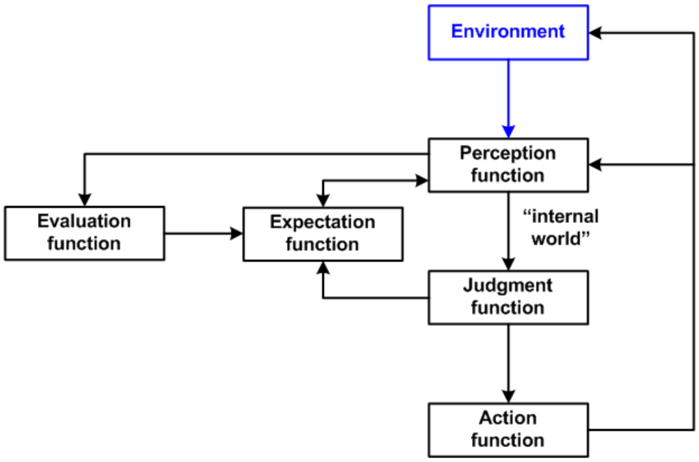

Figure 13.9: Judgment and evaluation loop model.

dissatisfactions in the sense of the *Wohlgefallen* and *Mißfallen* terminology introduced earlier.

As for the formation of an expectation function, if this function is to be capable of supporting cognitive appraisals, it must clearly interact with the subject's perception function. Thus, as figure 13.9 shows, the overall process involves numerous feedback loops, and therefore implicates a recurrent neural network system structure. (A neurological candidate for such an organization is a model proposed by Damasio [DAMA1-2] and called the convergence zone model. In order to include the affectivity factors, this model would also have to be augmented by neurological structures Damasio calls somatic markers [DAMA4-5] or something like his somatic markers).

Returning to figure 13.8, once a cognitive representation of Obs.OS(1) has been formed, along with a related expectation function of figure 13.9, it becomes the basis for reciprocal assimilation of the two action schemes (not cognitive assimilation, but merely practical sensorimotor assimilation) to form a higher and better equilibrated structure. This new coordinated scheme is practiced upon different physical objects, i.e. different Obs.OS(2) observables, and here accommodations to the scheme are required (in order to handle different physical objects). Type-β compensations and the substitution coordinator function are required for this. In time, this makes possible the formation of the type-I interactions of figure 13.1 and, later, the type-II interactions of figure 13.2. Piaget described this by saying "cognizance moves from the periphery to the center," meaning that the subject first becomes aware of an observable and only later comes to conceptualize the actions of a sensorimotor scheme separately from concepts of the objects upon which the scheme is practiced [PIAG6].

How does all this play out in the network structures of the central nervous system? This is a question for which neuroscience does not yet have an answer. One possibility is that the supporting neurological structure is something like the organization proposed by Damasio [DAMA1-2]. According to Damasio's hypothesis, signal processing in the cerebrum is carried out by both feedforward (caudal to rostral) and feedback (rostral to caudal) projections to and from small neural formations dubbed ***convergence zones***. Figure 13.10 illustrates Damasio's basic idea in simplified form.

The detailed description of this overall system is provided in the figure caption. The main point we wish to emphasize here is the role of the convergence zones (CZs). CZ networks' primary jobs are: (1) the generation of ***binding codes*** that time-lock the firing patterns of upstream networks in the sensory cortices (type-I binding codes), and; (2) generation of temporally sequenced firing patterns involving the motor cortices (type-II binding codes). Type-I binding codes generate representations of objects through the time-locked firing activities of small ***feature fragment*** neural networks in the sensory cortices. Activity firing sequences of type-

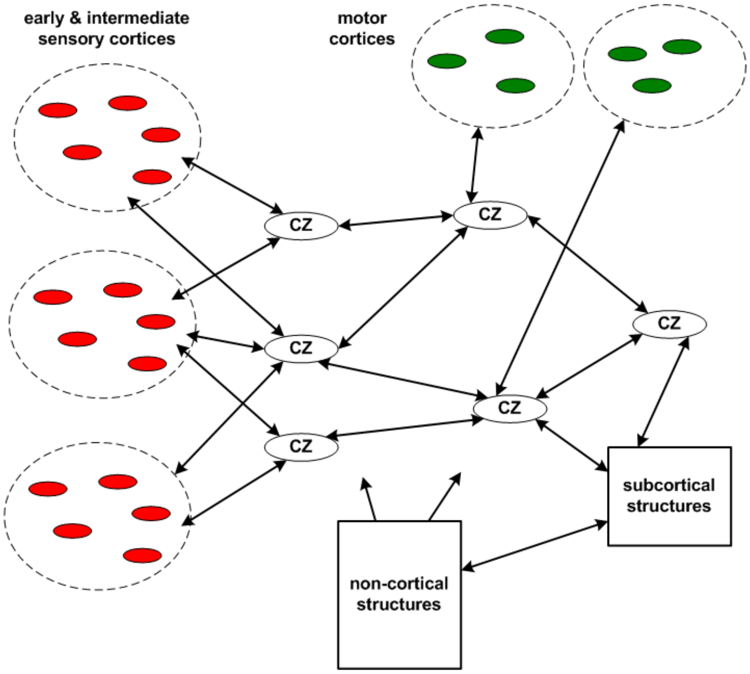

Figure 13.10: Simplified illustration of Damasio's convergence zone hypothesis. Small neural networks in the early and intermediate sensory cortices (red) make feedforward projections to small neural networks called convergence zones (CZs), and likewise receive feedback projections from these same CZs. These projections terminate over neuron ensembles rather than individual neurons. The binding of specific sensory networks ("feature fragments") through retroactive CZ feedback produces the representations of objects and events. CZs also receive projections from, and project back to, neural networks in the motor cortex. Finally, CZ projections to/from subcortical structures, e.g. the hippocampal formation, are also involved, as are activities in non-cortical networks, e.g. basal forebrain, brain stem, etc. Not shown in this simplified model, but necessary for Damasio's overall theory, are small CZ-like networks receiving input from amygdala and other affective subcortical structures in the brain. These are dubbed somatic markers, and the task assigned to them is "emotional" non-cognitive appraisal.

II binding codes not only instigate physical movements through the central nervous system's motor hierarchy but also, through CZ-mediated feedback to the sensory cortices, produce representations of events.

There is significant neurological research support for Damasio's model, but at our present state of knowledge its status is still that of an hypothesis. However, it is clear that, at least in principle, this neural organization has no obvious incompatibilities with the psychological models presented above, and it is clearly compatible with the actor-critic model structure if Damasio's "somatic marker" neural networks are included.

As of the date of this writing, no computational neuroscience research has been published regarding the Damasio model and its constructs. It is perhaps easy to appreciate why this might be so. As we have seen in this chapter, there is a great deal of integration required between the psychological models of structuring and scheme formation and neurological models based on a convergence zone type of system architecture. Such a model would have to present a vehicle for the constitutive coordinator functions and provide for the compensation behaviors. However, if this can be successfully accomplished, it opens the door for understanding the neural basis for Piagetian schemes, the actuality of which has been established through the work of developmental psychology. A successful model will also have to provide for the emergence of type-I and type-II interaction structures which, as we have seen, are dynamical sensorimotor, cognitive, and affective phenomena.

§3. Prelude to Network System Models for Partitioning and Structuring

The models presented in the previous sections stand at a very high level of our modeling hierarchy where psychology and computational neuroscience make contact. It has perhaps been very clear during the discussions above that at this level we are dealing with extremely complicated system phenomena. If a theory at this level is to be more than merely descriptive, it must employ network system models that meet up with the requirement of solving the stability-plasticity dilemma, that are capable of dynamical reorganization in their connectivities, and that can serve as recognizably correlated signal processing representations of the psychological models introduced in this chapter.

One thing that is clear from models such as Damasio's is the global role played by whatever solutions to the partitioning problem we may find or propose. The connectivity to and from CZ networks involves activity-driven adaptation of the connection strengths. This is partitioning writ large in the overall top-level view of neural organization. ***At the same time***, the self-organizing partitioning of the network systems does not go on independently of the *integration* or binding problem. As the psychological models presented earlier show, partitioning and binding are *both* part and parcel of the overall central process of equilibration. We would not be off base if we said ***partitioning relates to accommodation*** and ***binding relates to assimilation***. System level ***adaptation*** is aimed at bringing the two actions into balance, and so we cannot separate the partitioning problem and its adaptive processes from the binding problem and its adaptive processes. The common bond between the two is the structuring of functional schemes – an idea of psychology – and the functioning of network system models neuroscience believes to form the neurological substrate for the psychological phenomena.

We have now come to the point in this book where we are finally in a position to appreciate the general problem a comprehensive theory of high-level neurological organization must solve. Put another way, we are in a position to appreciate what a systems engineer would call the problem definition at the top level of the neuroscience hierarchy. The neurological correlate of a Piagetian scheme must be identified. The functional capabilities for coordinator functions and compensation behaviors must find expression in network system structures. Adaptation schemata must provide for the operation of interaction structures of type-I, type-II, and of the form presented in figure 13.8. All this must, at the same time, be capable of being given a *context* in a model such as that of figure 13.9. Finally, the resulting system model must be capable of interpretation in terms of ***action implications*** and ***practical meaning implications*** as discussed near the beginning of this chapter. Most of these requirements have not yet been met at the present state-of-the-science.

Some research progress has been made in this direction by the ART map models of Grossberg et al. In particular, Grossberg, Carpenter, and others have been able to find workable network structures that utilize interacting ART maps in which one map feeds back to and helps to control the "attentional" subsystems and "vigilance" functions contained in the ART map theory. (These pieces of the ART picture are the means by which partitioning is accomplished and the stability-plasticity dilemma is addressed in ART). However, we are not far enough along in this textbook to jump into a discussion of ART just yet. ART solves a very complicated theoretical problem in neural network theory, and so the solution method has many facets.

It is far better, from the viewpoint of pedagogy, to ease into ART theory in stages. This we will begin to do in chapter 14. In the material that follows, the reader is asked to keep part of his understanding anchored in the material we have discussed in this chapter, and not to lose sight of where we are heading in the flood of mathematical details we must deal with en route.