Am I Thinking Assemblies?

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1 What is the Physical Basis of Mind?

The Greeks have reduced the multiplicity of materials to a conceptually simple basis: a small number of atomic types and their chemical combination. Such conceptual unification has yet to be attained for the phenomena of mind. One of the important functions of our mind is the construction of models or "symbols" for external objects and situations. What is to be discussed here is the structure of the symbols of mind.

1.1 Regulative Principles

The discussion may gain in focus by contrast and analogy to the symbols of human communication. The following principles are formulated from this point of view.

1.1.1 Hierarchical Structure

The symbols of communication are hierarchically composed of subsymbols. For instance, a book is composed of chapters, paragraphs, sentences, phrases and words. Such hierarchical structure must also be required of the symbols of mind.

1.1.2 Full Representation

The symbols of communication are mere parsimonious, tokens for the images they are to evoke in the reader's mind. In contrast, the symbols of mind have to fully represent all aspects of our imaginations.

1.1.3 Physical Closure

Each written symbol of communication is represented by a dedicated piece of matter, e.g. a bit of ink on virgin paper. The symbols of mind have to coexist within the same physical system. New symbols should not require new pieces of hardware.

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1.1.4 A Basis for Organization

The symbols of communication are passive products. In contrast, the symbols of mind have to serve as the basis of active organization.

2 The Classical Framework

Currently, theoretical and experimental work on the function of the brain is dominated by a theory which is so common-place that it is rarely stated as such and that it even lacks a name. Let me refer to it as the “classical framework” or as the “classical theory”. Its essential tenets have been stated in the works of Hebb (1949) and Hayek (1952), although most of them are much older.

2.1 Semantics

Physical states of the brain are to be regarded as symbols for objects, situations, etc. What is the structure of these symbols and in what way do they refer to their subject?

2.1.1 Semantic Atoms

The complete symbol characterizing the present state of my mind can be decomposed into smallest units, Semantic Atoms. Each atom can be interpreted as an elementary symbol with its own meaning. Typical subjects for atoms are “a blue line of orientation $a$ and stereo depth $r$ at position $x$ of retina”, or “there is a face”. Semantic Atoms are represented in the brain by physical units (nerve cells or conjunctive groups of nerve cells). Atoms can be in an active or an inactive state.

2.1.2 Combination by Co-Activation

The complete symbol characterizing the present state of my mind has been composed by the co-activation of a number of semantic atoms. The symbolic meaning of the composite symbol is additively composed of the elementary meanings of the constituent atoms. The sets of co-active units are often called assembles, a term introduced by Hebb.

2.2 Organization

How are the symbols of mind organized, i.e., how do they come into existence? This organization proceeds in steps which are discussed in reverse historical order.
2.2.1 Logogenesis

Units, or atoms, are activated or inactivated by excitatory and inhibitory interactions. These are channeled by slowly changing (see Sect. 2.2.2) physical connections. There are two sources of influences on a unit: external and internal to the brain. The external influences are controlled by stimuli to the sense organs. The internal influences are controlled by the activity of other units. The symbols of mind are quasi-stationary assemblies, stabilized by the input and exchange of excitation and inhibition.

2.2.2 Ontogenesis

The internal connectivity patterns necessary to stabilize assemblies are created by synaptic plasticity. If an assembly is to be “written” into the system, connections between its active units are strengthened (Hebb plasticity). An assembly thus “stored” can later be recovered from partial input. This function is called associative memory.

2.2.3 Phylogensis

In order for the system to work in the way described it has to be placed in an appropriate initial state, with respect both to the basic machinery and to the initial connectivity. This initial state is realized with the help of information stored in the genes.

2.3 Two Remarks

An accurate and complete statement of the “classical theory” is impossible. As is the case with most fundamental conceptual frameworks, their basic tenets are implicit in all detailed work, yet are subconscious and sometimes inconsistent. The account given here of the “classical theory” therefore is necessarily an idealization.

In the ensuing discussion, the “classical framework” is taken as a comprehensive system for the brain as far as it is concerned with the symbolic representation of the (internal and external) world, although this claim of comprehensiveness is rarely made by anybody.

3 Critique of the Classical Framework

If I ask you to pass me that book over there — and you do so — you demonstrate a number of abilities of your brain: language interpretation, pattern recognition and visual scene analysis, planning of action, visuo-motor coordination and motor pattern generation. It has been tried, over decades, to understand and model those abilities and others within the classical framework, without much
success. The problem could be that no one has been able yet to find the right initial connectivity diagrams or the right set of trigger features to make the system work. It is argued here that there is a deeper reason for this failure, that the classical framework itself is to be blamed. Although my discussion seems to be philosophical in nature, the thrust of it is directed at the solution of technical problems. To put it in computer-language, without appropriate data structures one cannot write appropriate algorithms. This section raises a number of objections to the classical framework. The next chapter proposes solutions to the issues raised.

3.1 Semantics

3.1.1 The Assembly has No Structure

The mental symbol in the classical framework, the assembly, is a set of coactive units. As such it has no internal structure. [I should mention here that the lack of syntactical structure in the assembly has been criticised before by Legendy (1970).] Put the other way around, if two symbols (two sets of units) are made co-active, all information on the partition of units among the original symbols is lost. The classical symbol thus violates principle 1.1.1. It cannot be avoided to co-activate symbols, e.g. those referring to parts of a scene to be described. In such cases the features and modifiers which appertain to the simultaneously represented objects begin to float and form illusory conjunctions, i.e., they trigger consequences which should be reserved for objects combining the features differently. This problem may be called the superposition catastrophe of the classical framework (see Fig. 1).

There are various ways in which the classical framework has tried to avoid this difficulty. The most wide-spread of them consists in a severe restriction of the network to those connections which draw the right consequences. One important scheme is as follows (see Fig. 2). Keep the part-assembly in phys-

![Diagram](image_url)

**Fig. 1.** Superposition catastrophe. The box symbolizes some part of the brain, and is imagined to be filled with neurons. Each dot represents an active cell. On the left, there are two different sub-assemblies. On the right, the two sub-assemblies are superposed by co-activation. Information on the partition of the superposition into sub-assemblies is lost. The rest of the brain can only react to the whole assembly, not to the original sub-assemblies. False conjunctions of features will therefore lead to erroneous reactions.
ically distinct subregions ("boxes") within the brain (e.g., different parts of a topologically organized visual area); no confusion is possible so far. Have the pattern within a "box" classified by a set of specialized units ("cardinal cells"). Let the "boxes" speak to the rest of the brain exclusively with the help of those "labeled lines". The symbols within the boxes can interact with each other on a higher level without confusion because all detail is invisible on that higher level. Let me illustrate. If the linguistic part of the brain received a full list of the visual features seen at present, it would infer illusory patterns from false conjunctions of features. The presence of patterns has to be evaluated at a place, near to retina, where the relative positions of features are still known, and must be sent in encoded form to the linguistic part. Knowledge of the features is useless if it is not complemented with knowledge about their grouping into patterns. Therefore, visual features are to be hidden from the rest of the brain.

This solution creates more difficulties than it solves. Cutting the network into boxes severely restricts flexibility. It puts a heavy burden on phylogensis (if it is not possible to derive the box structure from a process of ontogenetic organization). Putting patterns (e.g., visual patterns) into boxes is a difficult problem itself (visual patterns may overlap on the retina). The scheme presupposes the existence of dedicated units to represent high-level patterns (e.g., "grandmother"). New patterns require new units (thus violating regulative principle.

Fig. 2. Avoidance of the superposition catastrophe in the classical framework. Assemblies are enclosed in boxes, A, a, b, ... . Active units are represented by filled circles, inactive units (in A) by open circles. Patterns within the lower boxes are represented, within A, by cardinal cells (labeled lines). Boundaries of boxes are not crossed by connections, except the ones shown. Especially, output from the lower boxes is provided exclusively by cardinal cells. The associative connections necessary to store and stabilize assemblies are restricted to within boxes. The hierarchy can be continued above and below. Patterns in different boxes can be superposed without confusion, since no unit is sensitive to co-activity of units in different boxes. However, the scheme creates great problems. It is difficult to attain one-pattern-per-box. All patterns have to be represented by cardinal cells; information beyond this classification is discarded. The restriction of connectivity as described is difficult to produce (in ontogeny or phylogeny) and is inflexible.
1.1.3, physical closure]. Awful administrative problems are involved in deciding when to represent a new pattern and in finding virgin units to represent them. All variable detail describing the patterns within the boxes (e.g., "grandmother has a good-humoured grin on her face and wears a blue hat") are stripped off on the way to higher levels, thus violating principle 1.1.2, full representation. In summary, the scheme only works in very restricted environments and with rigid patterns for which the machine has been specifically designed.

Another solution to the superposition catastrophe problem involves selective attention (Treisman and Gelade 1980, Crick 1984). The total symbol which is relevant to the actual situation is not simultaneously active. At a given moment, activity is restricted by a central-command system (directing a "spot-light") to a smaller subsymbol. Conjunctions are only permitted between units which are co-activated in one "fixation" of the spot-light. In this scheme, a history of consecutive fixations can express a symbol which is hierarchically structured into subsymbols, thus solving the problem in principle. Remaining problems with this scheme are with the generation of an appropriate history of activations [the special case of the activation of compact areas in visual space has been worked out in (Crick 1984, Treisman and Gelade 1980)] and with the evaluation of this history. Evaluation necessitates a temporal storage medium which can be sensitive to the whole history, i.e., to a comprehensive symbol.

3.1.2 No Assignment of Meaning to Connections

The classical framework assigns meaning to units. This assignment is possible on the basis of the special contexts in the external and internal environment of the brain in which the units are active. Connections are laid down by synaptic plasticity in response to coincident unit activity. Thus, in comparison to units, connections are tied to much more specific contexts. Accordingly, specific meaning could be assigned to connections. However, classical theory doesn’t do so. The reason is that individual connections are not expressed in the symbols (assemblies), and that connections aren’t dynamical variables (they cannot be activated and inactivated like the units). This point will be taken up below.

3.2 Logogenesis

Some readers may be inclined to shrug off semantics as an epiphenomenon, insignificant for the dynamics of the brain. However, the points of criticism raised in the last section materialize in terms of dynamics. The important point is that situations which are represented by indistinguishable states cannot be expected to lead to distinguishable consequences in the brain.

3.2.1 Interference by Irrelevant Connections

The point of logogenesis in the classical framework is to co-activate units which are part of the same context. This process is plagued by the presence of con-
nections which have been formed, and make sense exclusively, in presently irrelevant contexts.

In the associative memory scheme of the classical framework, this problem is solved statistically. A unit which should be on in a given assembly receives many excitatory connections from within the assembly, whereas a unit which should be off receives only a few connections, from those other units in the assembly with which it happens to be co-member in another assembly. This system works well as long as the assemblies stored in the memory have little overlap with each other. If, however, assemblies have large subsets in common they start to create strong shadows, partly activating other, overlapping assemblies. Now, overlap between mental symbols is the rule rather than the exception. Traditionally, one avoids the difficulty by introducing more units. If there are several units for each elementary symbol, different copies can be dedicated (together with their connections) to different assemblies. Thus, a given assembly gets rid of irrelevant connections by avoiding the activation of the units that command them.

This "solution" necessarily has an unwanted side-effect. The overlap between mental symbols is important as basis for vital generalizations. When I consider a particular scene, I absorb knowledge about the objects involved, by modifying the interactions within and between the corresponding mental symbols. I want to be able to have this knowledge at my disposal in other situations if they involve partly the same objects or aspects. This, however, is possible only through physical overlap between mental symbols. Avoiding this overlap destroys the basis for generalization.

What is needed is a system in which presently irrelevant connections can be switched off, precisely as the presently irrelevant units can be switched off. This would make connections the subject of "meta-interactions". Such a system is discussed in Sect. 4 below.

3.2.2 Overlay of Functions

This paragraph treats in fact a special aspect of Sect. 3.2.1. Neural modelers usually take the liberty of concentrating at any one time on one function of the nervous system, correspondingly dedicating their hypothetical neural hardware to that function. This is an understandable habit, but it hides the fact that all functions of which our mind is capable have to somehow coexist in the same brain. An obvious solution to the problem is the juxtaposition of dedicated hardware. As far as the functions are already known to phylogeny, this is a viable solution. However, many functions are learnt during ontogeny, and they naturally involve symbols which are partly identical. Functions are defined by appropriate systems of interconnections. While the system is performing one function, connections subserving other functions are highly disturbing. Ontogeny may be able to slowly separate the important functions physically from each other (e.g. by developing connections mediated by specialized units which are gated by excitation and inhibition). However, this will not always be possi-
ble (due to anatomical constraints), it will take time (during which an overlay of functions has to be borne), and it may not be desirable (since new functions have to partly use old functions). Again, it would be nice if there was a way to temporarily inactivate all connections subserving functions which presently are not relevant.

3.3 Ontogenesis

The term Ontogenesis is taken here in the special sense of referring to that part of structural genesis of our mind and brain which is shaped by our mental history. Those earlier parts of structural genesis which are under more direct control of the genes, and consequently of evolution, are counted under the heading of phylogeny. Ontogenesis speaks of the formation of memory. For this discussion it is advantageous to distinguish two types of memory, historical and structural memory. A similar distinction is made by many neurologists, although they refer to it by a variety of names. Historical memory allows us to store specific high-level knowledge, such as "Paris is the capital of France", and to recall specific events of our personal biography, complete with detail, circumstances and persons involved, thoughts we had at the time, and so on. Structural memory stores structure and knowledge in a way independent of specific contexts. The two types of memory serve different important purposes. They seem to be implemented by different structures or mechanisms in our brain [it has been shown that patients with amnesia, in whom the ability to lay down historical memory traces is destroyed, may still have structural memory (Cohen and Squire 1980)].

In the classical framework, memory is implemented by Hebb's rule of synaptic plasticity. It connects units which are co-active in a mental state. Let me first discuss structural memory. Certain co-activity relationships in the scene represented by the actual mental symbol are essential, others are accidental. The internal structure of objects is much more stable, and consequently more significant, than, for instance, their spatial relationships, which vary frequently. (This difference in significance of relationships in an observed scene is a direct reflection of the difference in strength of physical interactions within and among the objects making up the scene.) It is usually useless to couple two units which correspond to features which are part of different objects. Such connections, created by the indiscriminate stickiness of Hebb's rule, would soon clutter up the whole brain with unspecific connections.

In classical theory, there are two solutions to this problem. The first relies on the fact that physically non-existent connections cannot be plastically strengthened. It therefore suffices to restrict the physical network to such connections as can be expected to correspond to significant relations, resorting, for instance, to the box structure discussed in Sect. 3.1.1 and in Fig. 2. This solution is to be rejected with the same arguments as used in Sect. 3.1.1. The second solution permits all associations between the units active in a mental symbol, but puts connections under the constraint of competition (e.g. by limit-
ing the total strength of connections going into a unit or coming out of a unit). After sufficient statistics has been gathered, the strengths of connections will reflect the frequency with which they have been strengthened, and thus will reflect the significance of interactions. This solution takes prohibitive amounts of time. In reality we often have to base vital decisions on inspection of a single scene. Somehow, synaptic plasticity must be conditioned by a significance of relations which can be deduced directly from the structure of a scene. Such a system will be discussed below.

Historical memory seems to require the coupling of all units which happen to be united in the mental symbol to be memorized, so that an indiscriminate stickiness is required here. However, historical memory apparently cannot store just any conceivable situation, it seems to be good only for situations which are “legal” according to our structural memory (Bartlett 1932). It may therefore be useful to discriminate a “strong force”, which constitutes structural memory, from a “weak force” responsible for historical memory. The weak force becomes perceptible only if the mental symbol comes sufficiently close to one of the historical memory traces, in which case a large number of individually weak connections coherently add up to perceptible influences. Under ordinary circumstances, the weak force is nothing but an unimportant random perturbation. In any case, the existence of historical memory cannot distract from the conclusion that structural memory cannot consist in an indiscriminate stickiness, as is implied in the classical framework.

3.4 Phylogenesis

Throughout centuries, one of the great themes about the brain has been the balance between nature and nurture, between phylogeny and the more fluid types of organization, ontogeny and logogeny. The genetically determined brain is certainly not a tabula rasa. On the other hand, it is to be regarded a weakness of classical theory that for every function it is ready to invoke a specialized connectivity pattern, and that whenever it is difficult to explain it by ontogenetic mechanisms, it invokes genetic determination, i.e. it makes phylogeny responsible for it. This “phylogenetic loophole” is favoured by an important scientific idea, the algorithmic scheme (sometimes referred to by the adjective computational). It proceeds in four sequential steps: (1) identification of a problem; (2) formulation of an algorithm; (3) implementation (in a computer or in the form of a nervous network); (4) execution of the algorithm. If the scheme is applied to specific functions in the brain, it is only too tempting for the modeler to restrict his explicit presentation to steps 3 and 4 and to assign steps 1 to 3 to phylogeny. However, with a problem presenting itself to an individual for the first time in evolution, all four steps have to be performed by ontogeny and logogeny in his brain, and the role of phylogeny must be restricted to providing a “meta-algorithm”, the physical framework for the whole scheme, which includes the formulation of the problem and the “invention” of an appropriate “algorithm”! In other terms: we must not only understand how the brain performs
certain specific functions, but also how the brain finds them! If it is necessary to invoke specific connectivity structures (cardinal cells, box structures, gated pathways) we also have to specify the process of ontogenetic organization for it. Only structures of a general type can be put off to phylogeny.

3.5 Violation of the Regulative Principles

Assemblies as symbols of the mind violate all of the regulative principles stated in Sect. 1.1.

(1.1.1 Hierarchical Structure) The only subsymbols of an assembly are individual atoms. All information represented by the activity of an assembly can be stated by giving a list of active units (the order in the list having no significance). The absence of any intermediate levels in this “hierarchical structure” is most drastically illustrated by the loss in grouping information when several subassemblies are co-activated (superposition catastrophe, Fig. 1). Several stages of hierarchical structure are only possible if the multi-unit detail of one level is encoded by units (cardinal cells) on the next level.

(1.1.2 Full Representation) To avoid false conjunctions, all specification of intermediate objects in terms of sets of units must be hidden from the view of consecutive stages of processing. Objects are represented by cardinal units, i.e. by mere tokens. In communicating, parsimony forces us to abbreviate complicated structures and convey them by symbolic tokens. In the brain, the full structure of the objects represented should be made available to all subsystems, without being deformed and mutilated by the prejudices of a narrow and rigid coding scheme.

(1.1.3 Physical Closure) One of the striking performances of our brain is its ability to deal with new phenomena and problems. Apparently our mind can build up new symbols and new functional structures. If, as seems to be necessary within the classical framework, patterns and interactions are represented by dedicated units, new units must continuously be actuated. Whereas with communication, where each new letter is a new piece of paper and a new drop of ink, this creates no harm, it cannot be tolerated for the brain. New units cannot simply inherit structure from the sets of units they are to represent and from other patterns with which they overlap. All their connections must be specified from scratch. Moreover, there are terrible administrative problems with the actuation of new units. When is it time to create a new unit: when a new pattern appears for the first time? If not, how do I keep track of multiple occurrences before having a unit dedicated? How do I select a candidate unit which happens to have appropriate anatomical connections and which is not yet dedicated? When will I liberate units standing for ephemeral patterns? All of these problems could be avoided if patterns were represented by those units of which they are composed.

(1.1.4 A Basis for Organization) The classical framework starts with a very simple principle of organization, synaptic plasticity. Certain steps of organization have been successfully described on that basis, among them the formation
of feature representing cells and the formation of interconnection patterns to store and stabilize assemblies. However, the assembly as symbol of the mind forces to assume operations and interconnection patterns which are so peculiar that it is difficult to imagine the form of their ontogenetic organization, to say the least.

For all these reasons the classical theory does not deserve the status of a comprehensive framework for a theory of brain function — it cannot be accepted as a description of the physical basis of mind.

4 Natural Representation

My criticism of the classical framework raised above would be incomprehensible if it wasn’t complemented by some constructive response. I therefore give here a concise description of a different theoretical framework, which has been described in detail elsewhere (von der Malsburg 1981, Bienenstock 1985, von der Malsburg 1985).

The physical world is hierarchically structured into objects, their arrangements and their parts. There is no need for an object to be “represented” by a new type of “cardinal unit”. A coherent object is simply formed by cohesively binding its constituent elements (crystallites, molecules, atoms, elementary particles). The interaction between objects is not mediated by representatives. It takes in fact place as a direct interaction between the constituents. Correspondingly, one could think of a symbol system in which a pattern formed by a set of elementary symbols is represented collectively by — just those elementary symbols! Let me call this a natural representation. High-level symbols in such a system are just large structured masses of elementary symbols, interactions between high-level symbols are the summated effects of the interactions between “atoms”. In order for such a system to work one has to introduce degrees of freedom and interactions which allow the atoms to bind to each other in a flexible way. Both the physical world and the systems of visual communication use spatial degrees of freedom to bind elements and form aggregates. If, in the brain, atoms are to be identified with nerve cells, spatial degrees of freedom cannot be used, since nerve cells are immobile.

4.1 Temporal Correlations

Time is divided into two scales, a psychological time-scale (some tenths of a second) which is characteristic of mental processes, and a fast time-scale (some thousandths of a second). Mean unit activity evolves on the psychological time-scale, but the activity fluctuates around this mean on the fast temporal scale. Units bind to each other by correlating their activity fluctuations. A set of units can be bound into a block by synchronizing their fast activity fluctuations. Several such blocks can coexist if their activity is desynchronized
relative to each other: this is the solution to the superposition catastrophe. [Legendy has mentioned temporal relations as a solution to the syntax problem already (Legendy 1970).]

Fluctuations arise from an intrinsic instability of units. Correlations arise in sets of units which receive excitation from a common origin or which are synaptically coupled. [That nervous networks can process correlations has been discussed before by Sejnowski (1981).] The useless and trivial state of global correlation is suppressed by an inhibitory system.

As we know, correlations have important consequences for the activation of nerve cells: neurons are coincidence detectors! If two units are desynchronized with each other they cannot cooperate to excite a third unit. If they are synchronized, they can.

4.2 Dynamical Connections

4.2.1 Modulating Connections

Correlations are shaped by connections. If correlations are to represent variable bindings, connection strengths must vary. This function is called synaptic modulation. The excitatory connection between synchronized units is increased in strength, up to a maximum strength which is characteristic of the connection. (The set of maximum strengths for all connections defines the permanent network.) The excitatory connection between two desynchronized units is decreased in strength, down to the value zero. These changes take place on the psychological time-scale. If there are no signals in the two units, the connection slowly sinks back, within times characteristic of short-term memory, to a resting state, in which it conducts with a constant fraction of its maximum strength. [A different system for reducing the physical network to a sparse “skeleton” has been described by Sejnowski (1981).]

4.2.2 Meta-Interactions

Connections interact with themselves and with each other. A connection self-reinforces: the existence of an (excitatory) connection leads to correlation, which in turn strengthens the connection. Connections cooperate: connections between the same source and the same target help each other to synchronize the source with the target, and consequently help each other to grow, if they don’t differ too much in length (number of intermediary units). Connections compete with each other as far as they run against the boundary condition of excluded global synchrony. There exists, thus, a system of “meta-interactions”, to which was alluded above (Sect. 3.2.1).
4.3 Logogenesis

Classical theory has to work with very restricted permanent connectivity patterns in order to avoid confusion (e.g. patterns are allowed to converse with each other only through their cardinal units). These restricted connectivity patterns have to be formed during ontogenesis or even during phylogensis. With natural representation, highly specific connection patterns are formed during logogenesis, i.e. on the psychological time-scale. Two constraints contribute to the specificity of those connection patterns: the structure of the permanent network and the rules of the pattern formation process described in Sect. 4.2.2.

4.3.1 Connection Patterns

They are distinguished by sparsity of activated connections (due to the competition between connections) and by optimal cooperation between the surviving connections. Simulation studies (Bienenstock 1985, von der Malsburg 1985) suggest that connection patterns have topological structure, i.e. they can be decomposed into many “neighbourhoods” of directly coupled units which are coupled by sometimes long indirect pathways. (In a random graph any two units have fairly direct connections.)

4.3.2 Projections Between Patterns

Topological connection patterns can be combined, by sparse projections, to form larger topological connection patterns. Thus, rich hierarchies of symbols can be formed. An important special case is constituted by homeomorphic projections, in which two connection patterns of equal inner structure are joined to each other by a one-to-one projection of connections between corresponding units, thus forming a larger connection pattern. Projections between patterns replace the association between the representative units in classical theory.

4.3.3 Restrictions Imposed by Permanent Connectivity

Connection pattern formation is a highly spontaneous process. It has, however, to be influenced by memory. This is possible if the structure of the permanent network systematically favours certain connection patterns. In an extreme case, the permanent network among a given set of units has itself the structure of a connection pattern. In a less radical extreme case, corresponding to the classical associative memory, the permanent network is a superposition of connection patterns. Connectivity dynamics then has to reduce the superposition and recover one of the stored patterns. Unit-wise overlap between the stored patterns does not lead to confusion. In the extreme case, several connection patterns co-exist on an identical support of units and can still be selectively activated [this process has been simulated (von der Malsburg (1985)]. In general, permanent
connectivity just imposes certain "grammatical" rules on the form of possible connection patterns, leaving great freedom to the patterns formed.

4.3.4 The Evaluation of Correlations

What are the dynamical consequences of the correlation structure of the signals emitted by a given set a of units? Suppose the set of units has permanent sparse projections to a number of other sets of units. a can excite activity in one of the other sets only if the correlation pattern on a fits the structure of connections in that other set, because only then the individual signals sent by a can cooperate with the help of inner connections in the other set. In addition, the signals coming from a select that connection pattern on the other set of units which fits the connection pattern in a. Different correlation structures in a thus establish resonance with (and arouse activity in) different sets of units.

4.4 Ontogenesis

Plasticity increases the permanent strength of those connections which are strongly activated. (It is probably necessary to require in addition that new connections be formed between cellular processes over small distances for cells which are strongly correlated.) A compensating process must decrease connections (and finally break them) under appropriate conditions.

This type of plasticity is far from being an indiscriminate stickiness, because two units are permanently connected only after having been bound to each other in a connection pattern. In other words, a new connection is stored only if it is stabilized and validated by existing indirect connections: it is already decided by logogeny whether a particular connection fits the context. In comparison to the classical framework, ontogeny has to carry a much lower organizational burden.

4.5 Semantics

4.5.1 Atoms plus Relations

A sentence cannot be described by an "unstructured sum" of the symbolic meanings of the letters in it (or even of the words in it). The order of the elements establishes relations. These relations are as much carriers of meaning as the elements. (Any message has a standard distribution of letter frequencies if it is long enough, so that information is contained exclusively in the system of neighbourhood relationships!) Natural representation, i.e. the representation of a pattern by its elements, is possible only if relations of the elements within the patterns are represented as well. In the system discussed here for the brain, the general type of relationship can be interpreted as common membership in sub-patterns (where the sub-patterns can overlap). If the whole pattern is the visual description of a scene, units may represent local visual features, and
relations bind those features to each other which apply to the same object, to the same part of an object, or to a local neighbourhood. (If the individual feature units are not specific as to retinal position, the patterns of activity and of relations among the units are then position-invariant representatives of visual patterns.) If the whole pattern is a linguistic structure, units may represent phonemes or morphemes and grammatical roles, and relations bind the phonemes or morphemes into higher units, attach grammatical roles to them and assemble those elements into phrases and sentences. Any mental symbol can be further specified by attaching modifying symbols to it. This attachment has to be made precise by specifying to which part of the symbol each modifier applies. The mental symbols which constitute our thoughts are huge systems of cross-referenced active units, all having vague meaning by themselves, creating precision only in their structured ensemble.

4.5.2 Symbols to Whom?

The symbols of communication are sent by one individual and are received by others. Who is the recipient of mental symbols? Let us leave aside the behaviourist answer, that the only recipient is the motor output, i.e. those sub-symbols which form in the motor modality of the brain. We rather have to ask, who is the subject of perception, and, how is the unity of perception established in the brain? It is an ineradicable misconception that the unity of perception has to be established in a separate center, which in addition is often imagined as being of structureless unity itself. This mental archetype leads to infinite regress and to absurdity. Instead, the unity of mind has to be seen as an organic equilibrium among a great multitude of elements. The mental symbols both send and receive at the same time. Signals sent by one sub-symbol are deciphered by other sub-symbols, and the sending symbol can in turn only establish itself, momentarily, if it responds to the messages and questions sent by others. In the state of unity, each subsymbol encodes in its own terms the situation described by the others. This unity is not reached by leaving out detail but by uniting all detail with the help of relations.

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