Introductory Remarks on Theoretical Neurolinguistics

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1. Introduction

There is widespread agreement among linguists that the empirical basis for languages is to be found in the utterances of the speakers of a language and in the psycho-physiological mechanisms which produce and interpret these utterances. However, since Saussurean structuralism and until Chomskyan generativism most linguists also agree that utterances and psycho-physiological processes should not be studied directly; study of the structure of language—"la langue" or competence—should instead have methodological priority.

I myself shared this assumption until a few years ago. In a discussion with psycholinguists and neurolinguists I argued that we should first attempt a clear understanding of language structures by means of our well-established and well-understood methods of structure analysis and that only after having reached satisfactory descriptions and explanations we could study performance processes in cooperation with psychologists and physiologists.

I changed my opinion since. I think we cannot ignore the serious interest that psycholinguists and neurolinguists take in our results and we must make an effort to present our results in a form which is more accessible and descriptively nearer to their approach. Moreover, I think that the difficulty of a procedural linguistics is largely exaggerated by structurally minded linguists; a procedural linguistics that is close to the problems of neurolinguists will not be too complicated, as I am trying to show in my current research. I would therefore argue for a revision of the linguistic position which so far favored the analysis of formal, non-procedural structure.

The proposed revision is not without precedent. On the contrary: It should not be forgotten that one of the most eminent linguists, Roman Jakobson, always had an open mind for all procedural and concrete aspects of language and his research on linguistics and neurolinguistics is of great importance. In several influential publications he tried to correlate linguistic dimensions—such as the syntagmatic-paradigmatic distinction and the distinction between structurally mediated language units and immediate sound phenomena-with the functions of parts of the brains—such as front vs. back, left vs. right—(see recently R. Jakobson, 1980).

In contrast to Jakobson's approach analyzing linguistic dimensions on a physiological macrolevel, I am proposing a procedural analysis on a micro-neurolinguistic level where neurons and basic neuron-networks, such as cortical columns and column arrangements, play the essential role. In this article I shall present a few, very simple examples from syntax which could illustrate what is aimed at. I think that ultimately, after having developed the essential components of such an approach, linguistics would gain an additional empirical basis: We could relate our results not only to empirical judgements about the well-formedness of utterances—i.e. the input-output conditions of an interpreter—but also to the evidences gained by research into his internal structure.

Before going to discuss the details of my examples, let me briefly indicate the essential neurophysiological evidences which led me to believe that neurolinguistics on the microlevel is possible. Hubel and Wiesel, two eminent physiologists, have shown how the processing of visual information transmitted to the brain is processed in the cortex. The essential processing is executed in a so-called column system. A column system is an arrangement of several columns, each of which is a network of neurons that cooperate to produce a specific result of the incoming information. The typical column systems as discussed by Hubel and Wiesel (1979) consists of a two-dimensional arrangement of 2×18 columns as represented schematically in *figure* 1. It is a part of the visual cortex containing many such column arrangements, one for each retinal spot. The column system combines two sets of properties of a line or edge of a visual object as perceived by the retinal spot: 18 possible orientations and the two possible eye-dominances (light-from-the-left and light-from-the-right). If one assumes that the first column pair (as represented in figure 1) corresponds to the vertical orientation of a line perceived, the light coming from such a line from the left half of the visual field causes the firing of the neurons of the column marked L in the figure and the light coming from the right half causes the firing of the neurons of the column marked R. Obviously, the column system provides for a combination of the properties from two sets of properties.

As linguists we are immediately reminded of the analysis of meanings into conceptual components: A procedural implementation of such an analysis would obviously require an operative system similar to the one found in the visual field. We are also reminded of the classical morphological analysis into paradigms, i.e. categories (or sets) of notional properties such as gender, number, case, tense, etc. Couldn't we assume that operations for componential analysis or morphological feature combinations may also be realized in the brain by column arrangements? Couldn't we assume that that part of the brain that is responsible for semantic processing contains a column arrangement for the concept triple male-adult, female-adult, non-adult and a concept sequence of human, bovine, galline etc. triggering the words man, woman, child; bull, cow, calf; rooster, hen, chicken etc. (cp. e.g. Lyons 1968:470). And in morphology, couldn't we assume to have combinations of the gender concepts with the case concepts realized by column arrangements? (See below for the explicit operationalization of this combination).

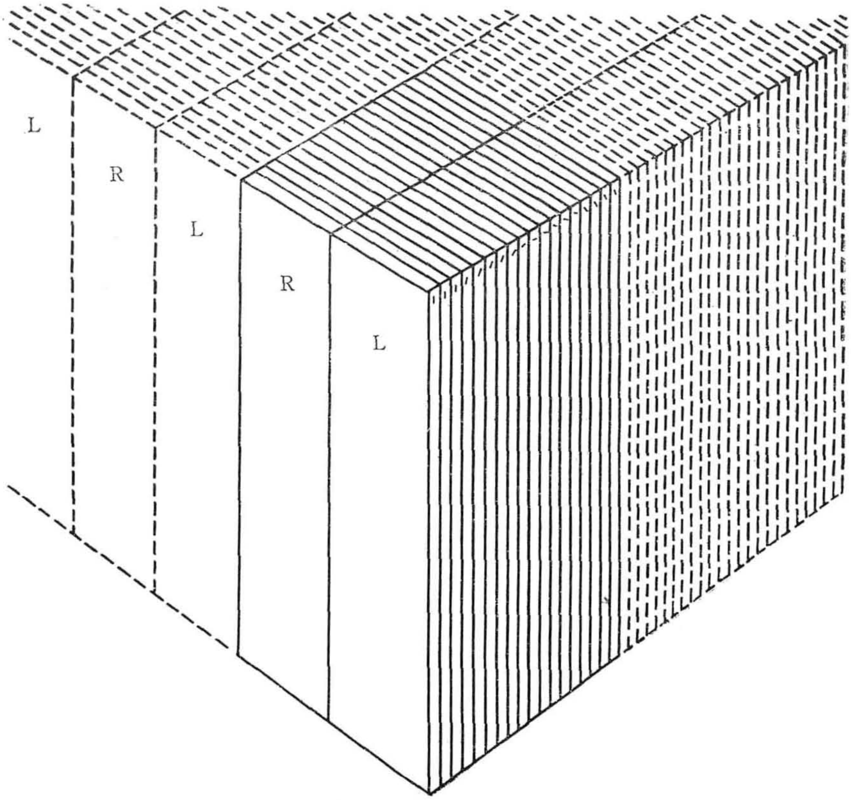


Fig. 1: Columnar block of cortex from primary visual cortex (cf. Hubel and Wiesel 1979: 142)

This assumption is not as speculative as it may seem. Indeed, neurophysiological research has shown that language processing parts of the brain consist of arrangements of columns (see Geschwind 1979: 166).

The question arises whether we could formulate the parts of a grammar including semantics—and, perhaps, all of language competence—as a network of neurons, where columns and column arrangements play the role that has just been suggested. The present article will discuss the first analytic steps to be taken in this direction. Details of physiological realization will be discussed elsewhere (Schnelle, 1981) and the neurophysiological description of more complicated syntax operations which include embedding and transformations is in preparation as well as the discussion of the realization of phonetics and phonology. As will be shown in the present article the operative network for syntax can be formulated with three types of operative nodes, the first corresponding to a more-dimensional array of column arrangements, the second corresponding to a one-dimensional arrangement and the third to a single column.

In spite of the fact that the operative realization of my proposal is rather unfamiliar it can be introduced in starting from very familiar types of grammatical descriptions. In this article we shall start from the familiar notations of a constituent structure grammar. We shall assume that a simple syntax is given. The notations used are usually understood to express rules for the rewriting of symbol strings. In contrast to this, we shall interpret the notations in a different way which requires several steps: The notations for a grammar are first schematically translated into diagrams. The nodes in the diagrams will then be given an operative interpretation; according to this the diagrams can be understood as operative networks which, by a rearrangement, can be directly read as column networks. These column networks can finally be interpreted as neurophysiologically specified column arrangements.

The analysis of structural and procedural aspects of language production can therefore be made on six systematically interconnected *levels of analysis* representing the steps of the interpretation of the symbolic notations:

1. Symbolic notations of grammatical systems
2. Connectivity diagrams
3. Operative diagrams
4. Operative networks
5. Columnar networks
6. Neurophysiologically specified column arrangements

In a sense to be explained in the article, 1., 2., and 3. can be considered to be *notational variants* of each other. The same holds for 4. and 5. Furthermore, 4. and 5. provide a "*finer*" *analysis* than 1., 2., and 3. in the sense that units of the former are substituted by the circuitry of the latter.

It is, however, important to understand that the translations into the levels 2. to 5. correspond to the symbolic notations under 1. *in a schematic way*. The linguist working on a particular empirical problem of syntax, and not interested in the operational details, needs to be concerned only with these symbolic notations of "rules" in more or less the same way as he is at present.

2. Operative linguistic diagrams: A first example

2. 1. I shall now illustrate by a few examples how symbolic diagrams are translated into operative diagrams. Let us start with an extremely simple example, the grammar G1 consisting of the notations presented in *figure* 2a. In ordinary constituent structure grammars only constituent rules like R1, R2, and R3 are represented (without the primes at the NPs in our representation). Rule R4 indicates that an NP may be activated either from the occurrence of an NP stemming from the use of rule R1 (hence a 'NP) or from the use of rule R2 (hence a ″NP). In a constituent structure grammar this rule R4 is thought to be implied by the usual operative interpretation of constituent structure rules as rewrite rules. As already indicated above, we do not assume a rewrite interpretation for the symbolic notations; the notations are not really rules in our sense. Since the term rule is, however, very much established, we shall speak of rules, where necessary. It should be understood, then, that the term is used metaphorically.

2.2. As a first step in providing a neurophysiological interpretation of these representations we present the *connectivity diagram* corresponding to the four rules of our grammatical system G1 as in *figure* 2b. The principle of correspondence between the grammatical system of G1 and the connectivity diagram is easy: ***Each symbol denotes an arc and each rule denotes a node*** in the diagram. The nodes are numbered by the numbers of the rules in the grammar.

The way in which constituent structure rules determine *constituent structure trees* is well-known. It is clear that G1 generates only one such tree and it is easy to see how the tree generated is related to the connectivity diagram (see figure 4a below).

The reference to the tree recalls a topological convention used in the interpretation

G1: R1: S→′NP+VP R4: {′NP,″NP}→NP

a) R2: VP→Vb+″NP

R3: NP→DET+Nn

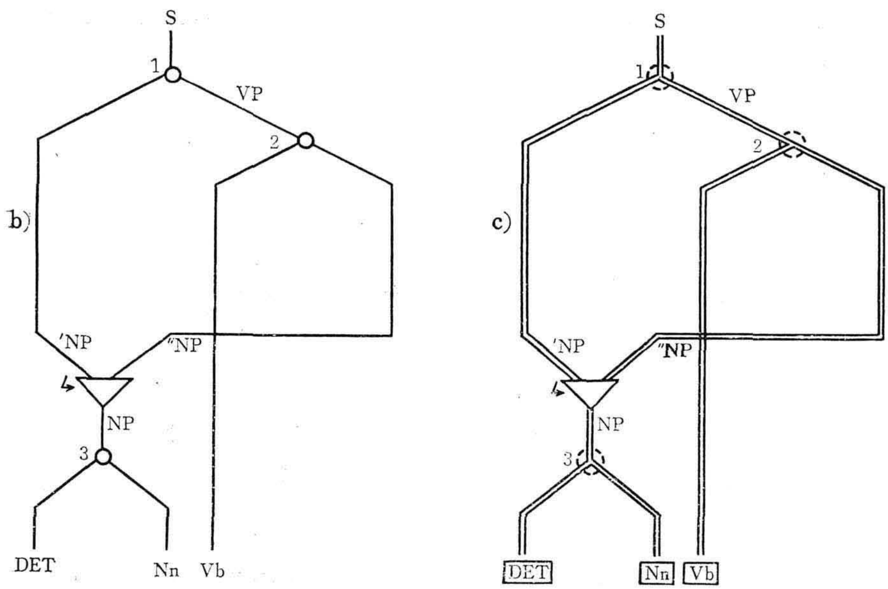


Fig. 2: a. The "rules" of grammar G1
b. The connectivity diagram for G1
c. The operative diagram for G1

of the trees, a *convention* which is to hold also *for the connectivity diagram*: The arcs of the diagrams should be considered as oriented from top to bottom of the page on which they are represented. Moreover, the arcs connected to the nodes representing a constituent branching (i.e. representing constituent rules, i.e. rules containing the symbol '+') are ordered from left to right. The procedural sense of this latter convention will be made explicit immediately.

2. 3. We are now ready to take the second step of our analysis which consists in the substitution of the connectivity diagram by an *operative diagram.* The method of substitution is again very easy. It consists in a substitution of every arc by a pair of parallel arcs of different orientation, the left one being directed from top to bottom and the right one being directed in the opposite direction, i.e. from bottom to top. Furthermore, the nodes of connectivity diagrams representing constituent rules (those containing the symbol '+') will be substituted by line arrangements as represented in figure 3*. These substitutions take care of the left-to-right convention mentioned above for connectivity diagrams (and trees). In general, the direction of the arcs should be indicated in the operative diagram; however, where the directions are obvious by top-to-bottom arrangement they may also be omitted (keeping in mind the convention made). As a last operation the end points of the connectivity diagram at the bottom will be replaced by black box representations. These black box representations are to be understood as promissory notes for further analysis in terms of diagrams or networks. The operative linguistic diagram resulting from our very simple grammatical system and its connectivity diagram is represented in figure 2c.

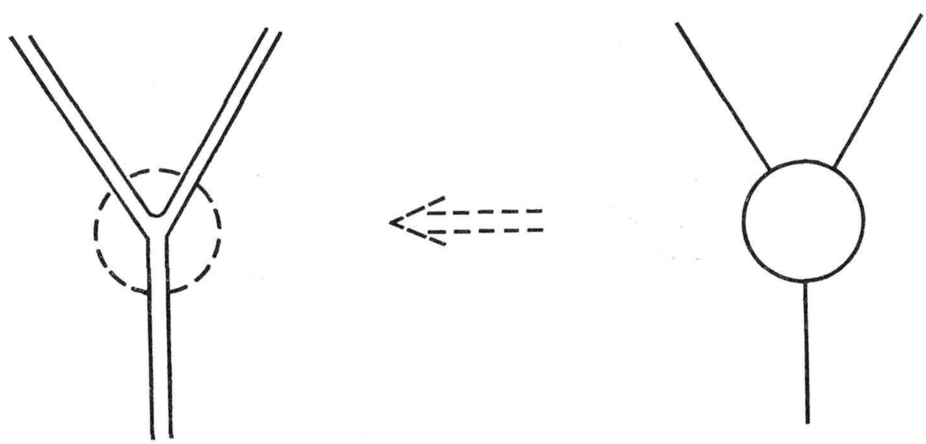


Fig. 3: The essential step from a connectivity diagram to an operative diagram: The elimination of the sequential node.

* To readers familiar with parsing algorithms: This corresponds to a top-to-bottom and left-to-right strategy as will be seen from the use made of the arcs.

This diagram already leads very far in the direction of the intended neurophysiological interpretation: The arcs emerging after the connections of the constituent nodes have been made (replacing these nodes by sequential order relations) will finally be ***interpreted as*** *intercolumnar axones* (either intra- or inter-hemispheric ones). The remaining *node corresponding to rule R4 represents a storage place for choices* in the processes determined by the grammatical system; they will be represented by certain *column arrangements* still to be specified. Finally the black boxes stand for cortical areas whose internal structure will be specified by the analyses of the black boxes by diagrams and networks. This analysis will have to render in particular the procedural aspects of phonology and phonetics.

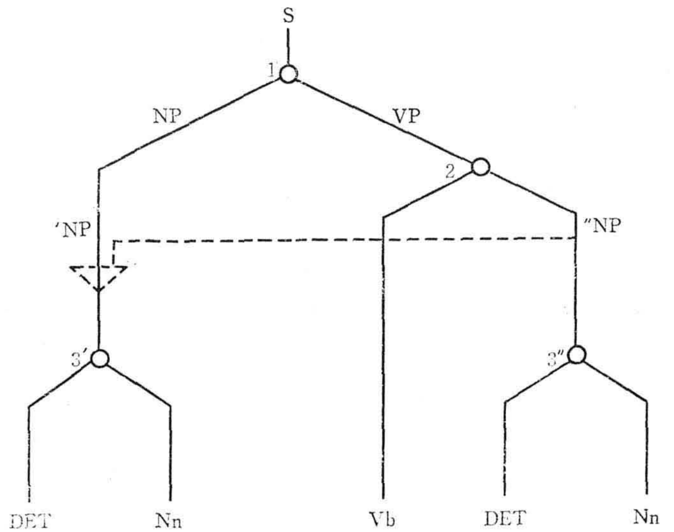
2.4. In view of the intended interpretation in terms of nerve nets and axons we may invest the resulting operative diagram with a *procedural interpretation*. The travelling of a neuron signal along the axon will be rendered in an operative diagram by the travelling of a signal over an arc of the diagram. Indeed, the procedural meaning of the operative diagram can best be understood by discussing the *flow of signals* occurring on it during an occasion of use of this diagram, i.e. during the production of the phrase described by the grammatical system which the operative diagram has been derived from.

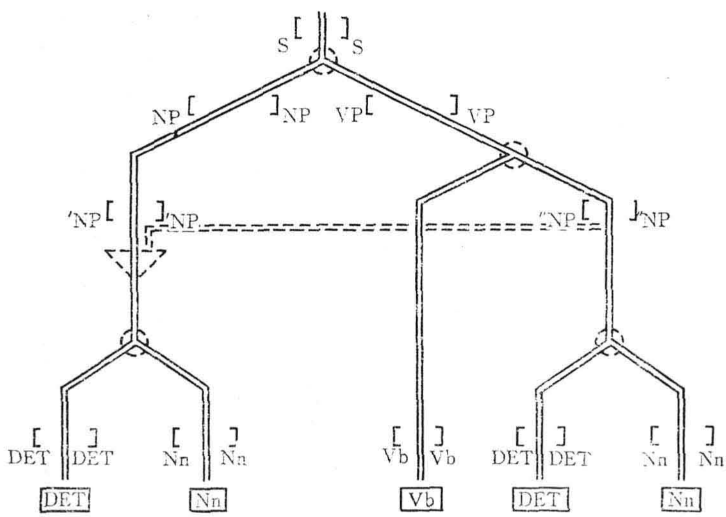
In the case of our simple operative diagram the process is as follows: The process is started by a signal on the left arc of the pair of arcs marked "S". This signal travels down the arc until it comes to node 4. At this node the information is stored that the signal arrived from the left. The signal is then transferred to the "arc" below from where it travels further down to activate the small black box generating a *Det*. After this black box has operated it returns a signal which is placed on the right wire above the black box *Det*. From there it travels immediately to the black box *Nn*. When the latter has executed its task it returns a signal placed on the right wire above *Nn*. This signal returns to node 4. Depending on the information stored there it will be transferred to the left *or* right output of this node. As already remarked above, the last information stored was "left" since the node 4 had been entered from the left. Therefore the signal is returned to the left. It travels back right to the top and then again down to the black box *Vb*. After this black box has produced a verb it returns a signal which travels again to node 4 entering this node from the right this time. This fact is "remembered" at the node. The signal travels down activating again *Det* and *Nn*, one after the other, returning to node 4. Due to the information stored the return signal is now switched to the right and from there it travels upwards until it reaches S, indicating that a structure of type S has been produced.

It is obvious: The sequential order of operation, represented in rules by

⌜· · → · · + · ·⌟

is rendered by the specific connectivity in the operative linguistic network obtained from the circled nodes in the connectivity diagram and the alternative made explicit by rule





c)

[[[.] [.]] [[.] [[.] [.]]]]
S NP DET DET Nn Nn NP VP Vb Vb NP DET DET Nn Nn NP VP S

Fig. 4: a. The relation between the structure tree for G1 and the connectivity diagram.
b. The operative diagram unfolded and marked by brackets.
c. The structure analysis in terms of bracketing expressions.

R4 is rendered by an operative node which is able to store one bit of information.

Additional insight into the structural meaning of the procedural aspect can be derived from the following considerations: We may label the arcs of figure 1c as indicated in figure 4b. The *labelled bracketing expression* represented in figure 4c is nothing else than an indication of the sequence in which the arcs labelled by brackets are used by the signal travelling over the operative diagram of figure 2c as just indicated.

Before proceeding to the next step in the interpretations leading nearer to neurophysiology, it will be necessary to introduce some slightly more complicated grammatical systems whose analysis requires types of operative nodes not yet exemplified by our first example. Furthermore, it will be necessary to illustrate on at least some level of complexity the possibilities our model offers as a grammatical system. The discussion of more complicated examples illustrating e.g. self-embedding and transformations will be deferred to the second part of this article, as already mentioned above.

3. Operative linguistic diagrams including lexicon and morphology

3.1. The situation becomes much more complicated when we add the lexicon and morphology to the grammar, in particular for languages with a more complicated morphology such as German. I shall now present the grammatical system G2 for the production of German sentences with transitive verbs only but nouns (and articles) with two gender and case alternatives. They will only be presented in the form of the connectivity diagram (see fig. 5) since the corresponding operative diagrams are determined schematically from them. The reader may still have difficulty to follow in detail the processing in this diagram; he should then study the more elaborate version of this presentation in Schnelle (1981).

Let me just discuss the three important types of nodes in the diagram. To the left below node 1 at the end of the edge labeled ″NP there is a node represented by a bold face dot. At nodes represented in this way simultaneous signals are sent. In this case one signal will travel down the edge ″NP, the other along the hyphenated line Vb-Lex. This latter signal triggers—at a node of choice type—a choice in the verb lexicon which selects in our example simply from the concepts of ***treffen*** and ***begegnen*** (both rendering a meaning alternative of to meet) the first governing the accusative case, the second the dative case. Depending on the choice either a signal determining the setting of accusative at the article production is sent along line A (simultaneous to a signal triggering the word morphology of the verb—below in the diagram) or a signal is sent along D setting the dative case. These signals set the rectangular node marked GEN/CAS. This node provides at its output all possible combinations of a gender and a case alternative. The actual combination is determined by the verbal government specification, as just indicated, and by the gender signals determined by the choice in the noun lexicon. This rectangular node is a node that by later translations of the diagram will be rendered neurophysiologically by a two-dimensional column arrangement.

As we see, we encounter five types of nodes in our connectivity diagrams:

1. Sequential nodes (rendered by small circles)

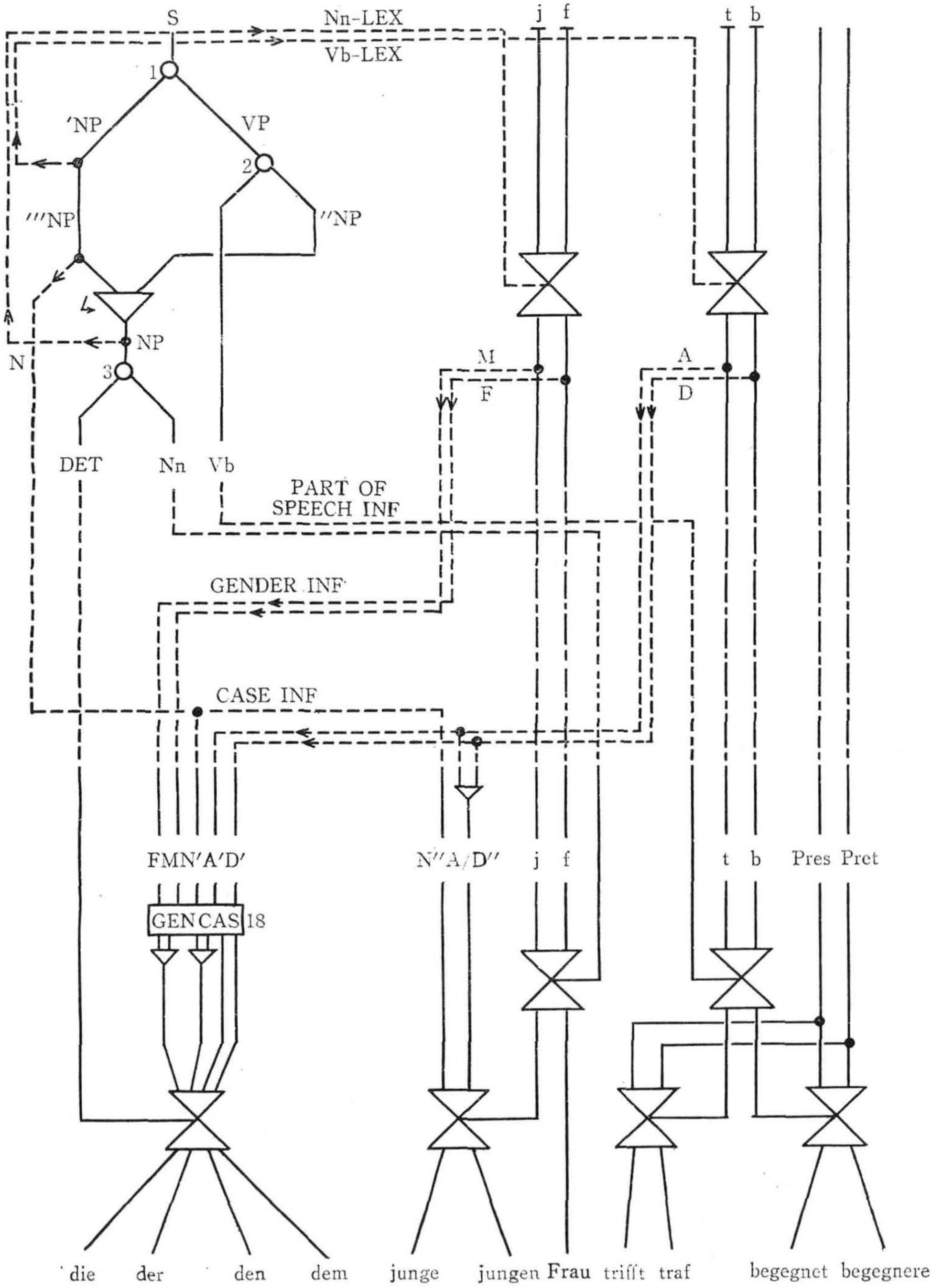


Fig. 5: The connectivity diagram for G4

2. Simultaneity nodes (rendered by bold face dots)
3. Alternative store nodes (rendered by triangles)
4. Alternative nodes (rendered by double triangles)
5. Paradigmatic field nodes (rendered by rectangles marked by the dimensions of the field)

Now, sequential nodes are eliminated in the operative diagram by the sequentiality of connectivity (as shown above) and the alternative nodes can be shown to be represented in a similar way. Essentially, we are, therefore, left with three types of nodes, the most complicated one being the paradigmatic field node, the alternative nodes being one-dimensional reductions of it and the simultaneous node being its zero-dimensional reduction. The reader who is interested in studying the internal structure of these nodes in terms of operative networks and column arrangements should consult Schnelle (1981). There the further steps of analysis leading to the neurophysiological interpretation are discussed in detail. The present article is only intended to give a first introduction into the operative ideas of a grammar conceived as a system of signal flow. In this introduction the notations of a rewrite grammar are only reinterpreted in a new way. Since, however, this reinterpretation leads to a level of analysis, the neurophysiological level, where new methods for an eventual falsification become available, it may well be that further research can lead also to a revision of the currently accepted notations and assumptions of grammars. But this requires much closer application of the methods just introduced. It seems to me, however, that bridging the gap between abstract rules of grammar and concrete processes of signal flow, in brains or machines, provides for a fruitful development of empirical research in linguistics.

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