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RISØ

On the Structure of Knowledge – a Morphology of Mental Models in a Man- Machine System Context

Jens Rasmussen

RISØ-M-2192

ON THE STRUCTURE OF KNOWLEDGE -
A MORPHOLOGY OF MENTAL MODELS IN
A MAN-MACHINE SYSTEM CONTEXT

Jens Rasmussen

Abstract. The report is a working paper which describes and illustrates different forms of mental representations of the functional properties of a physical system as found in a man-machine system context.

The outlines of a morphology of such models are discussed in terms of different levels of abstraction related to physical form; physical function; functional structure; abstract function; and functional meaning or purpose. The distinction between deterministic quantitative models based on variables and relations, and causal, qualitative models based on objects or functions which have properties and interact by events, is discussed. The dependency of the different levels of abstraction upon representation of aspects of the material basis of the system versus aspects of human reasons for the existence of the system is described. Finally, the different strategies of humans to cope with complexity is briefly discussed in the context of the morphology.

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PREFACE

This is an interim report with the aim of supporting an on-going discussion in a group of system scientists.

The subject area of the group covers analysis of control system structures for process plant automation; human operator modelling and man-machine interface design; and development of computer codes for systematic industrial risk analysis. The discussions of the group have frequently focused upon the need to formalise and harmonize the representations of the functional properties of physical systems which are the fundamental basis of the different studies.

In the present report, the morphology of models which appears from this discussion is described from the point of view of human operator modelling. The subject is discussed from a more formal, control theoretic point of view by Lind (1979), and the causal models applied for risk analysis are described by Taylor (1979). The hope is ultimately to develop a common and formalised morphology of models, which will serve an integrated approach to systems design.

The work is part of the inter-Scandinavian project on control room design and human reliability, sponsored by the Council of Nordic Ministers. Report No. NKA/KRU-P2(79)21.

INTRODUCTION

Many technical or industrial systems in modern times are highly automated and do not rely on human intervention in the control of normal, planned functions. Yet their existence depends on extensive support by a human staff to maintain the necessary conditions for satisfactory operation and to cope with all the badly structured and probably unforeseen states of affairs in the system.

In this role the human is supposed to act as a goal-oriented or purposive operator, and cybernetic models of humans are therefore often discussed. Such models suggest the control of the activity by feedback corrections from observation of discrepancy between intended and actual effect. The models are typically illustrated with reference to physical analogies in terms of servo-systems and regulators, probably to avoid resemblance to the miscredited teleological explanations. In their classical paper (1943) Rosenbluth and Wiener define teleological behaviour as behaviour which is modified <u>during its course</u> by signals from the goal. This restrictive definition seems, however, to be due to an inadequate distinction between the two concepts: <u>causes</u> of physical events and <u>reasons</u> for physical functions, a distinction which has been discussed in detail by Polanyi (1958). <u>Reasons</u> act as the classical "final causes" and can control functions of behaving systems by selection, be it natural selection or through human design choices; whereas <u>causes</u> control physical functions through the causal structure of the system. Since all technical systems are designed for very definite reasons, it directly follows that teleological explanations - in the classical sense - of the functions of man-made systems derived from their ultimate purpose are as important as causal explanations based on engineering analysis. The same is the case of explanations of purposive human behaviour.

Actually, even the human position and movement in the physical environment is only very occasionally directly controlled during the course of action by simple feedback. It may be the case in unfamiliar situations calling for accurate and slow time-space

coordination, but in more complex, rapid sequences, the sensory equipment is too slow for direct feedback correction, and adaptation is based on selection and recording of successful patterns of behaviour for use in subsequent situations, i.e., by forming an internal dynamic world model. Simple feedback control of human functions is probably most characteristic for the internal control of the physiological state of the organisms and during training of sensori-motor patterns.

Also at the psychological level most human activity depends upon a rather complex sequence of activities, and feedback correction during the course of behaviour from mismatch between goal and final outcome will therefore be too inefficient since in many cases it would lead to a strategy of blind search. Human activity in a familiar environment will not be goal controlled, it will rather be oriented towards the goal and be controlled by a set of rules which have proven successful previously. In unfamiliar situations when proven rules are not available, behaviour may be goal controlled in the sense that different attempts are made to reach the goal and a successful sequence is then selected. Typically, however, the attempts to reach the goal are not performed in reality, but internally as a problem-solving exercise - i.e., the successful sequence is selected from experiments with an internal representation or model of the properties and behaviour of the environment. The efficiency of humans in coping with complexity is largely due to the availability of a large repertoire of different internal models of the environment from which rules to control behaviour can be generated ad hoc. An analysis of the form of these internal mental models is important to the study of human interaction with complex man-made systems.

The following categories of models are based on an attempt to characterize and formalise the models found to be of importance for technicians in diagnostic tasks in the control rooms and the workshops of industrial plants. The concepts used in the different models span the range between concepts which are related to purely physical properties of the system which the man operates and concepts related only to the purpose of the system, i.e., the reason for its existence. This is clearly needed in

diagnostic tasks, since physical properties of a system deter-
mine <u>causes</u> of changes and only the <u>purpose</u> of the system is
able to supply references for proper function, or, in Polanyi's
terms, "rules of rightness".

The discussions of human representations of the environment
published so far have often been related to epistomological
problems in natural science (see e.g. reviews by Mihram, 1974)
and have consequently not been considering the purposive aspects
of the environment. The categories covered in such discussions
are not adequate to analyse human knowledge of man-made systems.
The internal representation of the environment used by human
problem solvers has of course been studied by cognitive psy-
chologists (see e.g. Neisser, 1976) and artificial intelligence
groups (Newell and Simon, 1972; Goldstein and Papert, 1977). In
these cases however, very general representations have been
discussed or emphasis has been laid on analysis of internal
representations in well defined task situations, such as games
or theorem proving which will not uncover the internal represen-
tations used for coping with the complexity of real life tasks
in man-made environments. The effectiveness of humans in such
situations is very probably due to the large repertoire of
different types of representation of the functional properties
of the environment which are at their disposal.

The benefits of analysing mental processes in terms of ex-
plicitly formulated mental models, strategies and data have been
discussed elsewhere (Rasmussen 1976, 1979). The present
discussion is focused upon functional models, i.e., internal
representations of the structure and functional properties of a
physical environment or system, hence the reference to the
"structure of knowledge". Knowledge of the properties of a sys-
tem can have other forms, such as state pattern models which are
snap-shots of coherent sets of observations, or implicit forms
like procedures which are rules for action upon the physical
world. The relations among functional models, state models,
strategies and procedures are illustrated in fig. 27 and briefly
discussed in the related text.

A TAXONOMY OF MODELS

The following discussion of the morphology of models is derived from analysis of protocols recorded during human operators' interaction with technical systems. A model is here defined as the internal representation of the properties or constraints in the environment which determine the interrelations among the data which can be observed from the environment. In mental activity, such models are used to predict future events and responses of the environment to human actions; to find causes for observed events; to determine proper changes in the environment to obtain desirable responses etc.

The categories of models stratify the span between the physical world on the one side, and human purposes, i.e., the reason for the existence of the physical systems on the other. However, it seems as if different categories of scientific theories also fit into this structure. For biological systems this is quite natural due to evolution by natural selection, since survival value can be seen as the reason for the observed functional structure of organisms. That theories of physical sciences fit into the structure is less obvious, but may probably be due to the fact that within physical science functional relations are studied which are emphasized by contemporary technological developments. The view that "the character of intellectual meaning is instrumental" was argued by Dewey (1925), and Smith (1977) supports the position: "Personally I believe that the internal structure of science was formed very largely out of the earlier factual findings of technologists ....". The reason for discussing the relation between mental models and formal scientific theories in the present context is, however, not philosophical, but the need for formalization of the different categories of mental models in the design of interactive man-computer systems. An attempt in this direction has been made by Lind (1979).

A tentative morphology of mental models has previously been presented (Rasmussen 1976, 1979); in the following sections the

structure and content of models related to different categories between physical realities and human purposes are discussed. The illustration of these categories is difficult, but attempts are made by presenting pictorial examples. The reader should, however, be aware that it is generally the content of the figures rather than their form which has explanatory value.

MODEL OF PHYSICAL FORM

Model of Monolithic Physical Form

A model of physical form represents the spatial distribution of matter in the environment; it is a portrait of the physical landscape. The model is monolithic if it is not structured in movable objects or parts, but is a recording of the spatial location of matter, only structured by the modalities of the sensing systems which are used for its recording: spatial location, form and size of fields or territories characterized by their colour, texture, temperature etc.

This level of modelling of the physical environment is the most objective, i.e., independent of the intentions of the modeller. Even then, however, is it dependent upon the intended use of the environment since this determines the resolution (naked eye, microscope, etc.) and modality of senses used for recording the information from the environment. Examples of this kind of model are static scale models, photographic pictures, eidetic imagery, etc.

In the human data processor, models of physical form of the environment serve as reference templates for recognition of individual faces and places; as subconscious maps for control of the elementary orientation and movement of the body in familiar environments. The monolithic model of the surrounding physical form is the basic spatial structure behind the more complex models of the environment at higher levels of abstraction or cognitive consciousness.
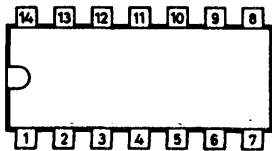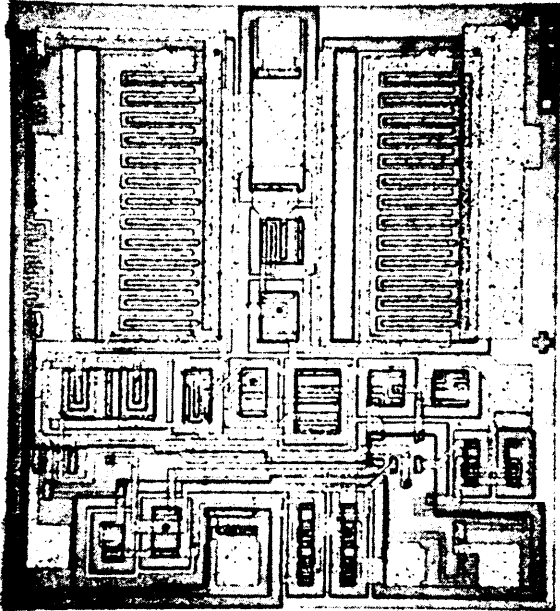
Fig. 1. Microphotography of integrated electronic circuit. Only the information on spatial arrangement of matter is significant to the general observer.

Fig. 2. Photography of traditional electronic circuit. To the uninformed observer this is a portrait of physical form. To observers with electronic background, this is hardly the case, as they probably will see a system of functional units - the picture presents a physical form structured in familiar objects or components.

Descriptions of humans in this domain can be illustrated by portraits and sculptures. Within natural science this is the level of for instance descriptive geology.

Models of physical form of technical equipment are illustrated in figs. 1 and 2.

Model of Structured Physical Form

To be useful, models of physical form are generally structured in generic elements and typical scenery, i.e., in objects and their spatial relations. Objects are compositions of matter which are frequently encountered; which can change their location without changing their formal characteristics; which are related to certain human tasks or activities; etc.

The way the physical form is structured into objects depends upon the intention or insight of the modeller. The environment can be structured into objects at varying levels of detail and certain physical aggregates can be free objects or part of the background depending upon viewpoint and human need.

The model can be generalized to represent typical objects, rather than the individual physical forms, in a schematized background or scenery. A highly familiar environment will be consciously perceived as composed of generic objects. The structuring of the physical form into objects therefore often implies a simultaneous transition from the individual portrait to the typical scheme. Examples are topographic and geographic maps as well as drawings and diagrams identifying physical objects and their spatial interrelation. See figs. 2 to 5. Models of man at this level are for instance anatomical maps and models. In the natural sciences, typical categories are descriptive geography, and descriptive taxonomies within biology (Linné).

The role of the structured model of physical form is a record of "where is what"; it links verbal names of things to their position in space. Structuring the environment in objects and labelling them according to need and intention is necessary to

MODELS OF STRUCTURED PHYSICAL FORM
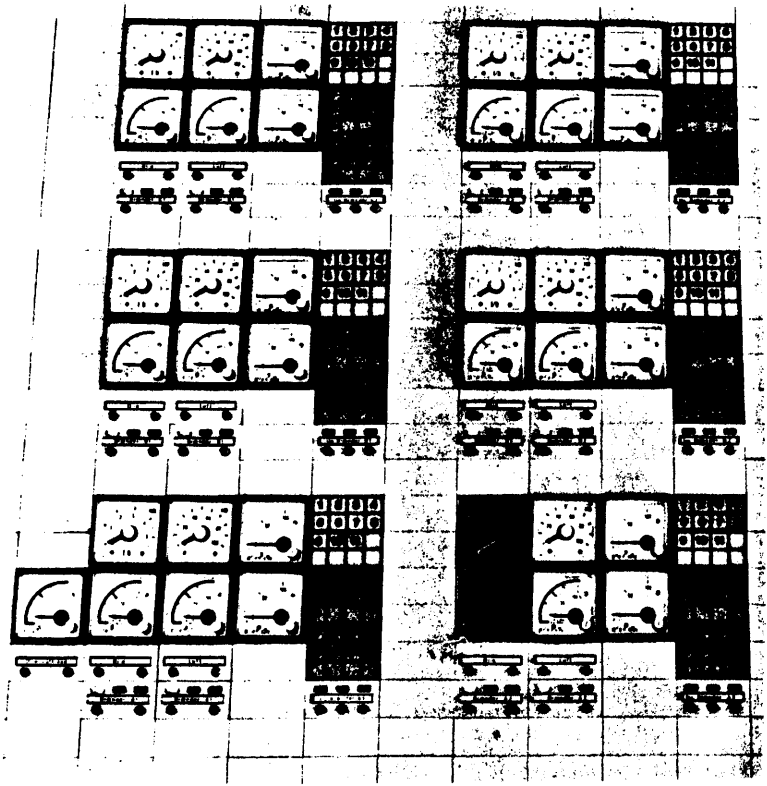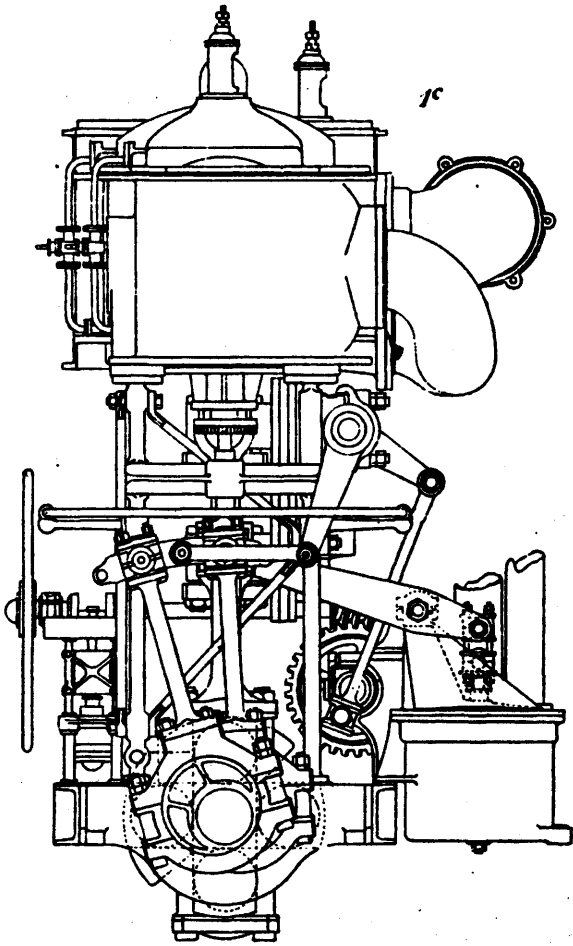
Fig. 3. Models of structured physical forms are important cognitive maps referring to where is what. (This physical form also carries symbolic information to those familiar with the purpose or reason. The form signals internal state).

Fig. 4. Simultaneously with structuring in components, objects, the model of physical form typically loses detail and portrait likeness; it stores a structure of generic elements.

Fig. 5. The purpose of or reason for a collection of objects can be so obvious that a model of physical form can turn into animated behavioural model. The observer adds the reason and functional properties implied.
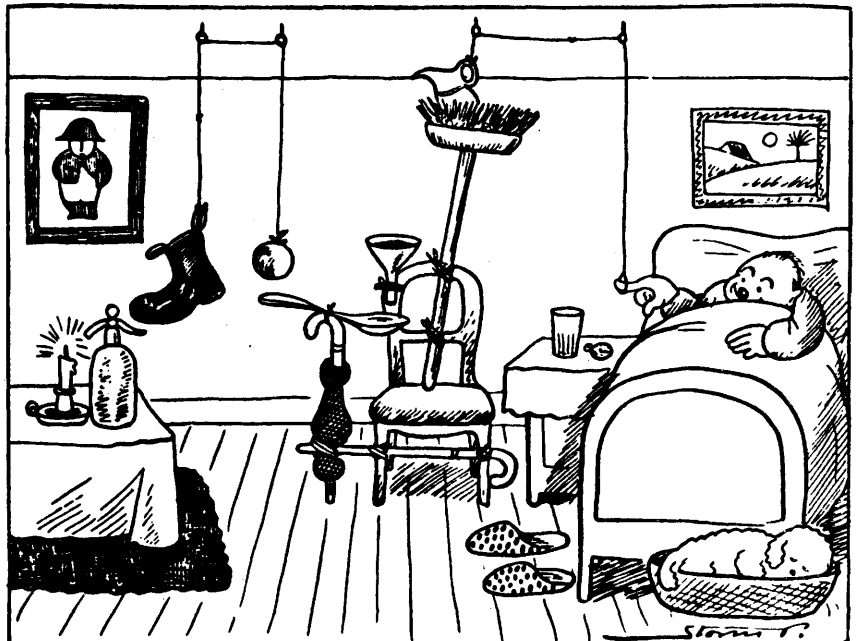
have an inventory for planning. The structured model of physical form constitutes a spatial map of tools and objects for action. Even though the structured and generalized model is used to plan the activity at the level of choosing means for manual actions, the monolithic model of the physical form of the environment is needed as "an individual portrait" for spatial control of the postural and positional movements of the body. The precision of this portrait of physical form probably determines the "manual variability", the degree of "clumsiness" in manual acts.

For human data processors, models of physical form probably have most significance for control of physical actions; they may also be needed at the cognitive level when the problem is to judge the spread of the effects of changes in the physical world, because the coupling of events basically depends upon the spatial properties of the environment.

Since the model of physical form represents the spatial, material physical world, it represents the physical conditions for purposeful function of a system - and therefore also the conditions or causes for missing functions, i.e., faults.

MODEL OF PHYSICAL FUNCTION

A model of physical function represents the physical structure of the system and its functional properties in terms of the objects, e.g. technical components, and their properties with respect to their mutual interaction.

Physical objects are separated from background by closed, non-overlapping boundaries. The level of aggregation or decomposition into objects, components, parts can be changed by rearranging such boundaries according to the need or intention of the human modeller or actor in the specific situation.

The functional properties are expressed as the potential for interaction, i.e., action and re-action among components and objects. This can be done in several different ways:

Behavioural Model, Dynamic State Pattern Model

The functional properties can be represented by a dynamic mapping of the position and shape of the relevant objects of the environment. The functional properties are then represented by the correlation in time and space of changes in the environment. This representation is dependent upon an active model which is able to simulate the behaviour of the environment; a kind of analogue spatial-temporal model whose elements are generic objects with typical patterns of behaviour which can be synchronized by means of signals from the environment. The efficient control of the interaction of the human body with the environment in fast sequences, for instance in ball-games or the western gun-men's "quick-draw", indicates the presence of such a model in a human data processor and reveals some important features:

- Feed-forward control of skilled patterns of movements.

- Simulation of the behaviour of the body and the environment in real time.

- Alignment and synchronization by selected, subconscious features of sense data.

- High precision, hence quantitative, analogue representation of variables.

- The simulation is performed in an active, distributed, i.e., parallel processing model.

The model controls the behavioural pattern below the level of conscious intention and it acts as reference in mismatch detection and attention control.

Causality plays no role in the model, except in the Humean sense of time-space correlations.

At the conscious level, this kind of model can be applied in case of "dynamic imagery", i.e., the behaviour of the environment is visualized, "foreseen". In this case, the state of the model can be initialized by verbal statements and activated by such, and thus the relation to the models behind natural language representations may be very close.

An important function of the subconscious world model is its control of the sensory equipment, which is continuously directed towards the focus dictated by expectations or experience, i.e., towards aspects which are known to be variable or uncertain or which have caused a mismatch. This kind of internal dynamic world model is necessary to explain why human observers also will notice omissions in the behaviour of the environment. Observed events may be absence of familiar occurrences.

Examples of this kind of model are difficult to illustrate. Basically, such models are active, dynamic material analogies for simulation. The internal dynamic world model of man can be realized by a pulse-density coded, distributed parallel processing logical network. Such networks have been suggested for high capacity analogue computers (Ribeiro 1967).

Structural analogue models can be represented by sequential process models in digital computers of sufficient speed and capacity. The important feature of analogue models in the present context is, however, their homomorphic representation of the environment. There is a one to one mapping of structures and processes. This feature is necessary to allow immediate and simple updating of the model in response to changes in the environment.

The data processes in simulation by means of an analogue model are determined by the structure and elements of the model and are controlled by general physical laws when the model has been initialized and activated. No sequential control algorithm is needed. Accordingly, this kind of data processing must be either

MODEL OF PHYSICAL
FUNCTION

Components/states/
events

Fig. 6. Schematic representation of the functional
structure of fig. 2. Schematic diagrams interrelate
symbols for components which, to the professional ob-
server, have well-known functional properties.

Fig. 7. Compare with fig. 4.

Fig. 8. Functional structure
of circuit of fig. 1.
Together with well-known
component properties it
forms a model of physical
function.

Fig. 9. Schematic diagram
of fossile power plant. When
used, component properties
are expressed qualitatively:
pumps circulate water, they
can stall etc., transistors
amplify; diodes clamp volt-
ages etc., valves open and
shut and fail to open etc.

simulated or represented by mathematical time functions. Several such mathematical models of selected functions of the subconscious dynamic world model have been developed:

Young (1969) describes manual control of vehicles, Curry (1976) and Sheridan (1976) model man's attention in monitoring task using optimal Kalman filters to represent the internal world model, Senders (1976) models the control of information selection by means of sampling and queueing theory.

This behavioural model has a special status in the taxonomy of models which is also evident from the part it plays in the context of fig. 27. First of all, it is an active model, it includes a processor and basically it should be classified as an animated model of physical form; it represents the form and time-space processes. (Also a model of physical form has a special status, since it represents the form at a specific time, it is a snap-shot and therefore also can be classed as a state pattern model). It is, however, convenient to maintain the "behavioural model" as a separate category to distinguish between high capacity, subconscious processes and the low capacity sequential processes based on conscious use of static models.

Model of Physical Function in Terms of Objects and Properties

Models of physical function used for conscious, sequential reasoning can be divided into two main categories: Models expressed in terms of physical objects with specific functional properties representing their potential for interaction, and models expressed in terms of variables and their functional relations. In the latter case, the state and behaviour of a system are represented by magnitudes of measurable variables, and their interrelation is represented by a set of rules specifying their interdependence. When models based on objects and properties are used, the state and behaviour of the system are represented by collective, qualitative variables in terms of states, events and actions. This leads to inaccurate representation of the magnitude of the individual physical variables, but at the same time to a precise representation of total, complex situations.

This is the case when the person is familiar with and aware of the context, i.e., his internal "behavioural" world model is properly updated and synchronized. The internal model can then support the interpretation of fuzzy, verbal state representations.

Examples illustrating models in terms of objects, properties, and events can be found in the semantic nets used to represent natural language reasoning in artificial intelligence programs (See e.g. Charniak and Wiks, 1976; see also Rieger and Grinberg, 1976).

In other words, to be effective in control of human interaction with a physical environment, the mental model in terms of objects, events and actions clearly depends upon the interpretive function of perception and the translating function of sensori-motor pattern of actions.

This type of model of physical function is based on stored rules and learned associations. The levels of object and event formation and formulation of intention for actions depend upon the level of skill. In case of difficulty, of lack of appropriate rules, the trick is generally to move to a more detailed level of objects which will then typically be more familiar, and to deduce the necessary rules at this level.

The cooperation of the subconscious, behavioural world model and a mental model of physical function in terms of objects and events is a characteristic of concrete reasoning in natural language. However, the same mode of data processing can be effective in abstract reasoning when the concepts are represented by verbal or graphic symbols. These symbols can then be manipulated like artificial objects which have properties and interact through events. The elements or concepts of a verbal representation can then be symbols for symbols or even higher order symbols, and their interpretation depends heavily upon the context defined by the internal world model.

The concepts of general languages such as natural languages or general purpose computer languages are much more complex than

the concepts needed for modelling the environment will be, if the level of abstraction can be explicitly defined and controlled. The difficulty in definition of the elements of natural language representations clearly appears in development of formal descriptions such as e.g. conceptual graphs (see Sowa 1976).

Models of a physical system in terms of objects and properties, states and events represent the functional possibilities. The purpose of or reason for the system is only represented by the actual selection of the present set of objects. The model can therefore be used for description of the possible functions - normal or abnormal - of a given system. The purpose of the system does not constrain the language used to describe it at this level, and changes in the system or its use are easily reflected by changes in the model.

Examples of models at this level are schematic diagrams inter-relating components which have familiar properties, see figs. 6 to 9; and semantic nets, see fig. 10. Natural language reasoning is found in cause-consequence charts, see fig. 11. In natural sciences, this is the level of description in e.g. Aristotelean physics, but also in modern science it is used to describe tools, circumstances and background for the selective descriptions at more theoretical or formal levels.

Models of Physical Function in Terms of Variables and Relations

When quantitative representation of the state of the environment is necessary, the state must be represented by a set of measurable variables. The functional properties of the system are then represented by sets of rules or relations interconnecting the variables. In this way, the physical components are dissolved into nets of relations between variables, and these variables are the "objects" of the data processing. The model is therefore in a way complementary to the models based on objects and properties; events and actions.

MODELS OF PHYSICAL
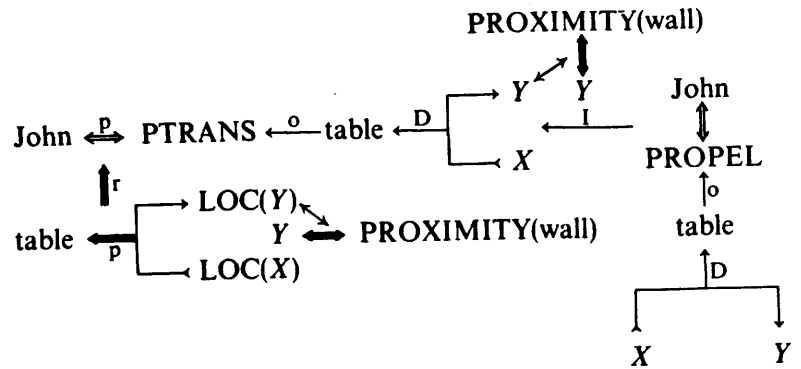FUNCTION

Objects/states/
events

Fig. 10. Semantic net representation of elements of natural language discourse - objects, events, states. "John pushed the table to the wall". Shank (1975).
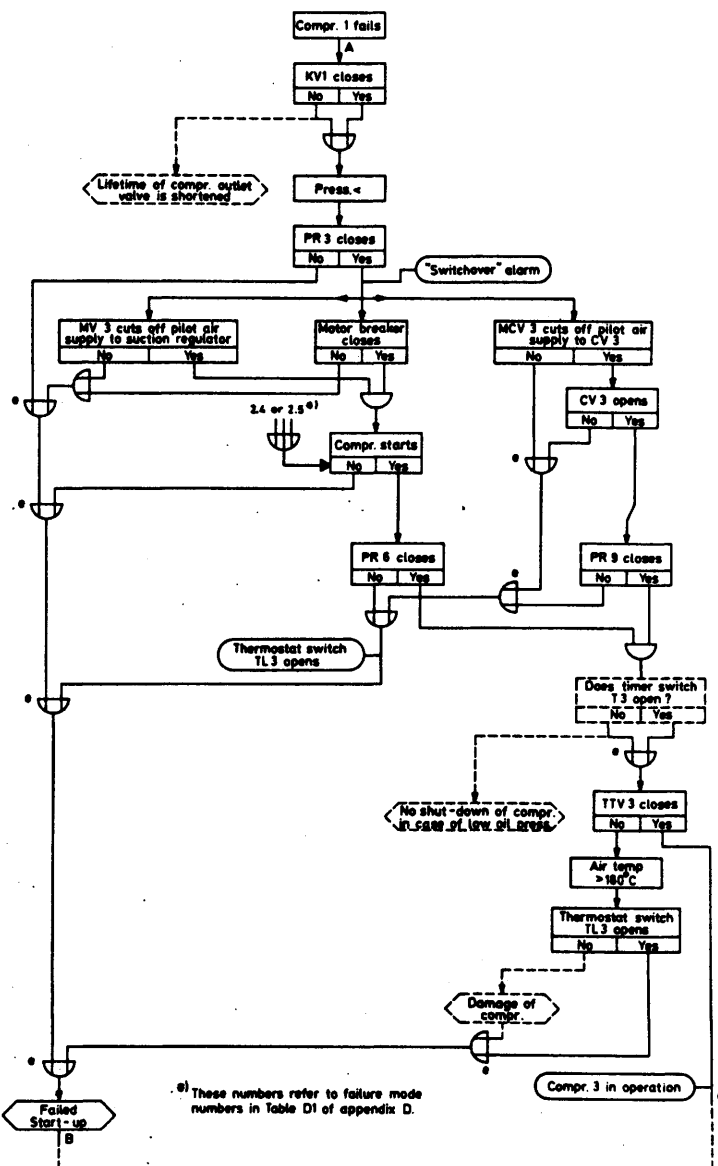

Fig. 11. A cause and effect diagram represents interrelation of potential events in a system. This is a stored set of if-then arguments derived from a functional model in terms of objects, properties and states, events. This is advantageous due to the close relation to physical events (faults). Nielsen 1977.

At the level of physical function, the variables and relations refer to properties of objects and parts with reference to the boundaries which delimit components and at which the variables are chosen. The variables will generally be incoherent sets of members of different physical categories, such as temperatures, pressures, positions, voltages, etc., and the relations may be expressed by calculating rules, mathematical formulas or by graphic means as (fields of) characteristics which are theoretically or empirically obtained, but which characterize a typical component.

This kind of representation is necessary during design to coordinate the interaction among components. The limiting properties of components and systems must be quantitatively expressed, and the corresponding variables must be controlled during plant operation with reference to such quantitative values. Measurement and display of individual quantitative variables is therefore important for adjustment of operation of a system to the proper, intended mode of operation.

However, presentation of the individual quantitative magnitudes of variables is closely related to a data processing model structured in variables and a net of relations. This representation is very difficult to use by operators in unsupported functional reasoning, since natural language causal reasoning will be based on objects, states and events. Unless measured variables are transformed into <u>symbols</u> which can be directly perceived in this language, an operator will typically use characteristic variables individually as <u>signs</u> for internal states of the system, i.e., each variable becomes a representation of a large set of variables.

Models of this category are illustrated by the examples in figs. 12 to 14. Variables/relations models are normally only used to solve isolated problems of very limited size, unless artificial tools (calculators; paper and pencil) are available to handle the numeric processing rules. At this level of models of physical function, relations are tied to individual or typical components, and they can be found empirically or derived from general rules at a higher formal level. They can be represented

MODELS OF PHYSICAL FUNCTION

Variables/nets of relations
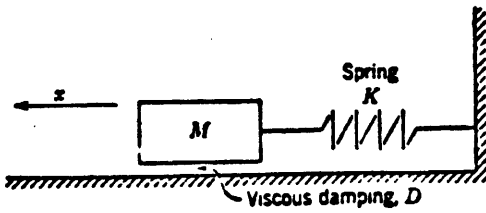
$$f = K(r_1 - r_2) \qquad f = M\frac{d^2r}{dt^2}$$

K = spring constant $\qquad M$ = inertia

$$f = D\frac{d(r_1 - r_2)}{dt}$$

x = displacement
D = damping coefficient

Fig. 12. Variables and relations describe inter-action of mechanical components. Note: the system is defined by pictorial representation. The general theoretical laws of this level serve as calculating rules.
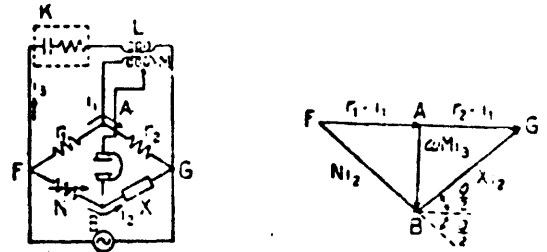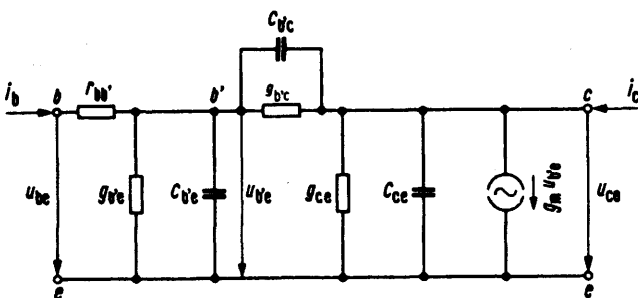

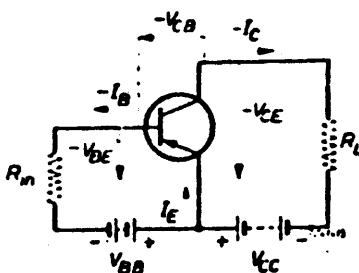Fig. 13. Functional model of a measuring bridge. Variables are represented analogically and relations by geometric conventions to support visual processing.
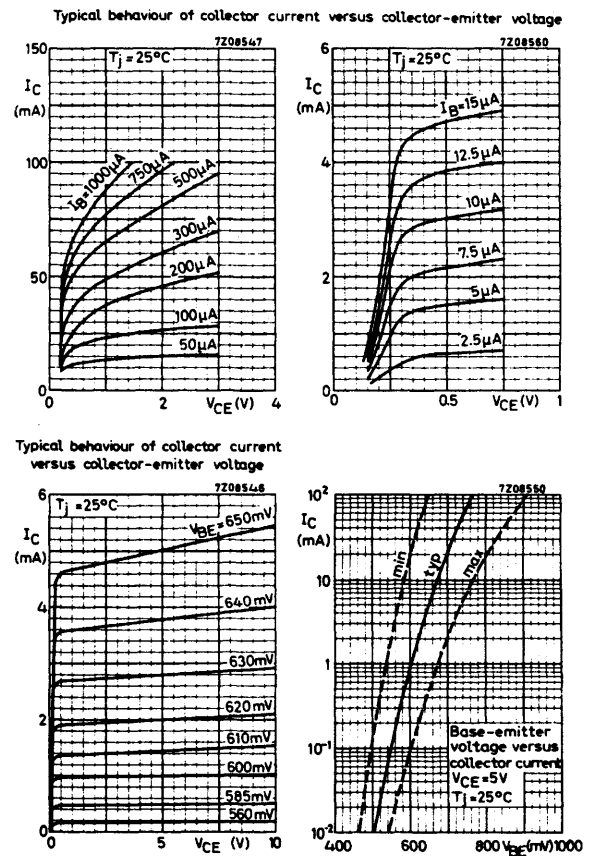

Fig. 14. Functional model of transistor amplifier stage. Relations are represented by field of characteristics, and visual manipulations are convenient. "Equivalent" diagrams facilitate natural language manipulation of internal transistor properties.

by calculating rules (Ptolemaean epicycles; Ohm's law etc.); by tables; or by graphic means. In unsupported reasoning, the quantitative variables will generally be discretized ("high", "low") or represented in relation to a reference ("a little higher than normal").

MODEL OF FUNCTIONAL STRUCTURE

Models in Terms of Variables and Relations

At this level of modelling the full consequence is taken of the disintegration of objects into nets of relations among variables, and the main element of the model structure is the "function", i.e. a set of relations among variables across boundaries of physical parts which is frequently met and generally useful irrespective of its physical basis. In a way such functions represent standardized, generic elements of system purposes. A model at this level is applicable for different kinds of physical systems, the use can be generalized and therefore models at this level of abstraction can support transfer of knowledge and experience between quite different systems. Examples of functions are "feedback loops", "cooling circuit", "p.i.d. control function" etc. The relations among variables can be expressed by calculating rules or graphically, as was the case for the quantitative model of physical function. The model of the functional structure is tied with system properties rather than component structures. Although generalized, this level of modelling still relates to variables which represent physical, i.e., mechanical, chemical, electrical properties of the system. The structure of the model does not necessarily reflect the physical structure of the system, but selected elements of its behavioural structure. This level is typically the level of scientific modelling and technical analysis. The rules or laws used to interrelate variables are general, system-independent laws, but they are expressed in concepts related to the physical system in question, e.g. the laws of Newton, Bernoulli and Ohm.

MODELS OF FUNCTIONAL STRUCTURE

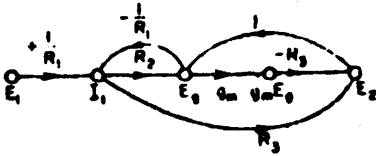Fig. 15. Generalized net of relations describing a transistor. Must be used together with the signal flow-graph conventions.
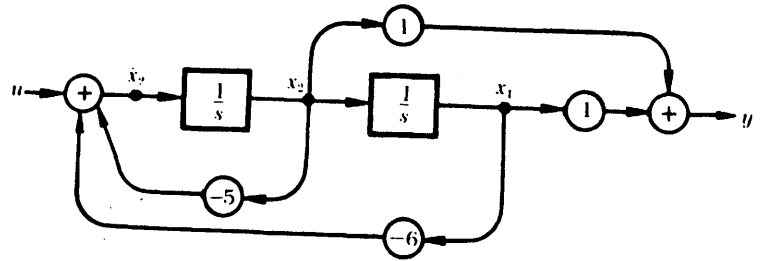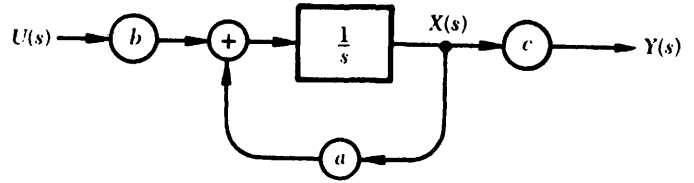

Fig. 16. Examples of generalized description of feed-back systems. Must be used together with control theoretic conventions.
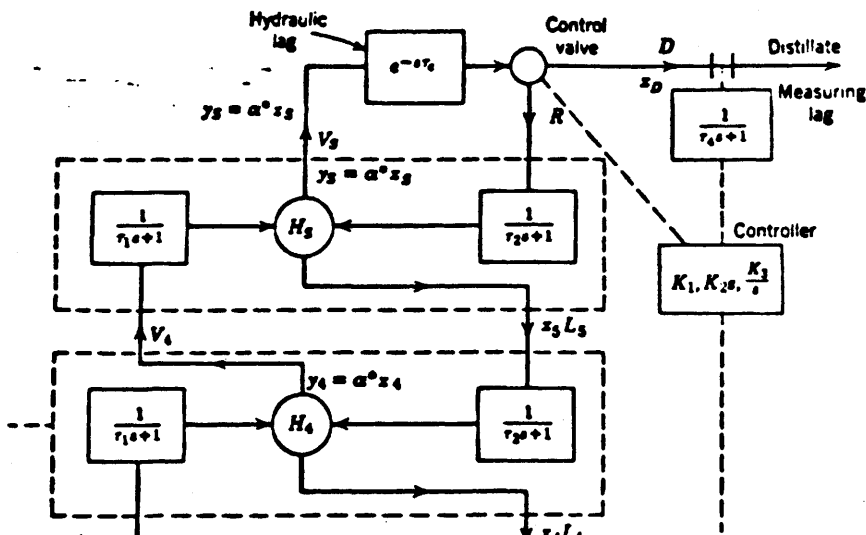

Fig. 17. Feed-back system properties represented by "time constants", a generalized representation of behaviour in time domain or frequency domain.

The boundary between quantitative models of physical function and those of functional structure is not too well defined. The distinction is mainly that the relations used in the first category are related to or embodied in physical components, whereas the relations in the latter category are totally independent of boundaries among components. Very often the "functions" at this level are overlapping aggregations of sets of relations from the lower level, being related to elementary purposes rather than physical elements. Examples are shown in figs. 15 to 17.

Models of man in this domain can for instance be quantitative physiological theories of metabolic functions and electro-chemical functions of nerve tissue. In psychology, some quantitative models of experimental psychology may be referred to this category of models.

Models in Terms of "Functions" and Their Properties

The efficiency of natural language descriptions based on collective variables in terms of states and events related to objects can be transferred to models of functional structures, if "functions" are considered "artificial objects" or symbols which are ascribed properties and potential for interaction and which respond to events and actions: Feedback loops can be stable, oscillating, respond to disturbances by overshoot etc.; cold slugs in boilers "lap up" steam; decrease of cooling result in "boil-out".

The efficiency of this type of model is due to representation of the functional properties of a system in terms of typical or "standardized" functional elements which are independent of their physical or material basis and of the specific system. Therefore, this representation supports transfer of knowledge of rules and empirical experience.

The functional structure of the total system can then be described by the interaction of typical "standard" functions which can often more easily be identified by an analysis or a decomposition of the overall purpose of the system in the light
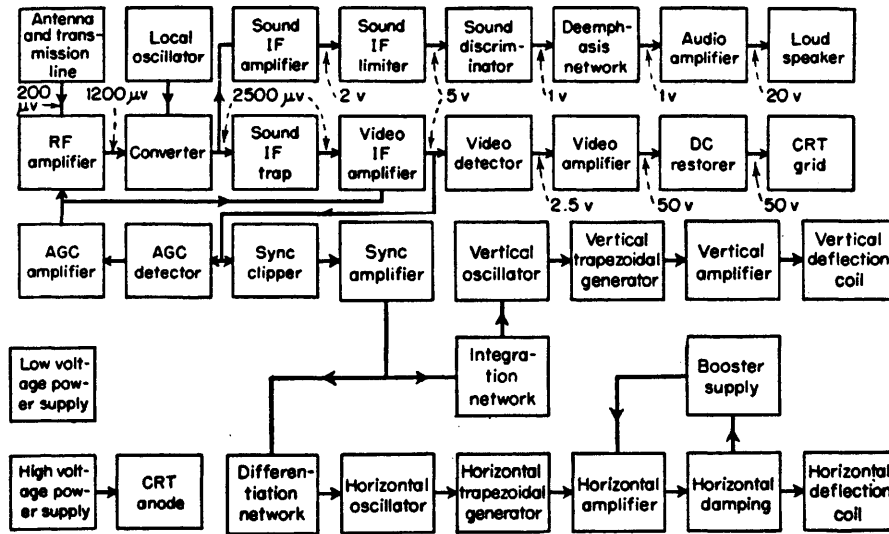
Fig. 18. Block diagram representing functional structure which does **not** necessarily represent physical structure.
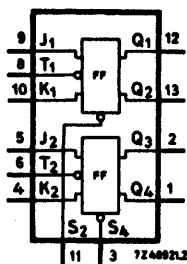

Fig. 19. This block diagram represents the circuit of fig. 8.

of the applied technology and design practice than they can be synthesized from their physical elements. This category of representations can be illustrated by "schematic block diagrams", figs. 18 and 19, which describe the functional structure of a system by means of functional elements, the properties of which are supposed to be familiar to a professional reader. In this category the typical verbal presentation of natural science theories is found together with most theories of traditional psychology.

MODELS OF ABSTRACT FUNCTION

The models of system structure and function discussed so far have the form of a structure of interactions among a number of typical components or functions. The system models are obtained by analysis which breaks the total system down into parts - physically or functionally - to a level where their behaviour and responses to changes are known or can be derived by familiar rules and relations.

To represent the overall function of the system by a consistent model, it is necessary to move up in abstraction level to a language which is independent of the local physical and functional properties; i.e., which depends on universal laws and symbols.

The overall function of a system must be represented by a generalized causal network, e.g. in terms of energy, matter and information flow structures. We are in the domain of Boolean algebra; the cybernetic laws of systems theory; and the laws of conservation of matter and energy. The laws and symbols form a consistent structure which is axiomatically true and therefore "device- and process-independent". Cassirer (1921) in his discussion of substance versus function characterizes the concept of energy as follows: "Energy is able to institute an order among the totality of phenomena, because it itself is on the same plane with no of them; because lacking concrete existence, energy only expresses a pure relation of mutual dependency".
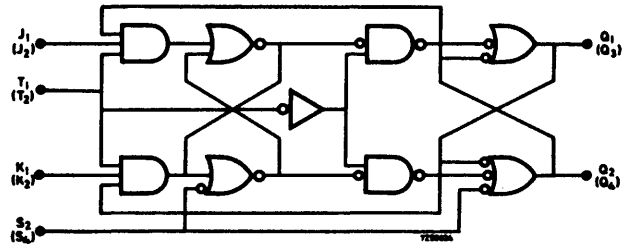
Fig. 20. Abstract function of the
circuit figs. 8 and 19. This func-
tion cannot be derived from physi-
cal analysis, but is derived from
purposes and reasons by means of
conventions, e.g. high voltage
level = logic 1, low voltage level
= logic 0.

———— mass flow path
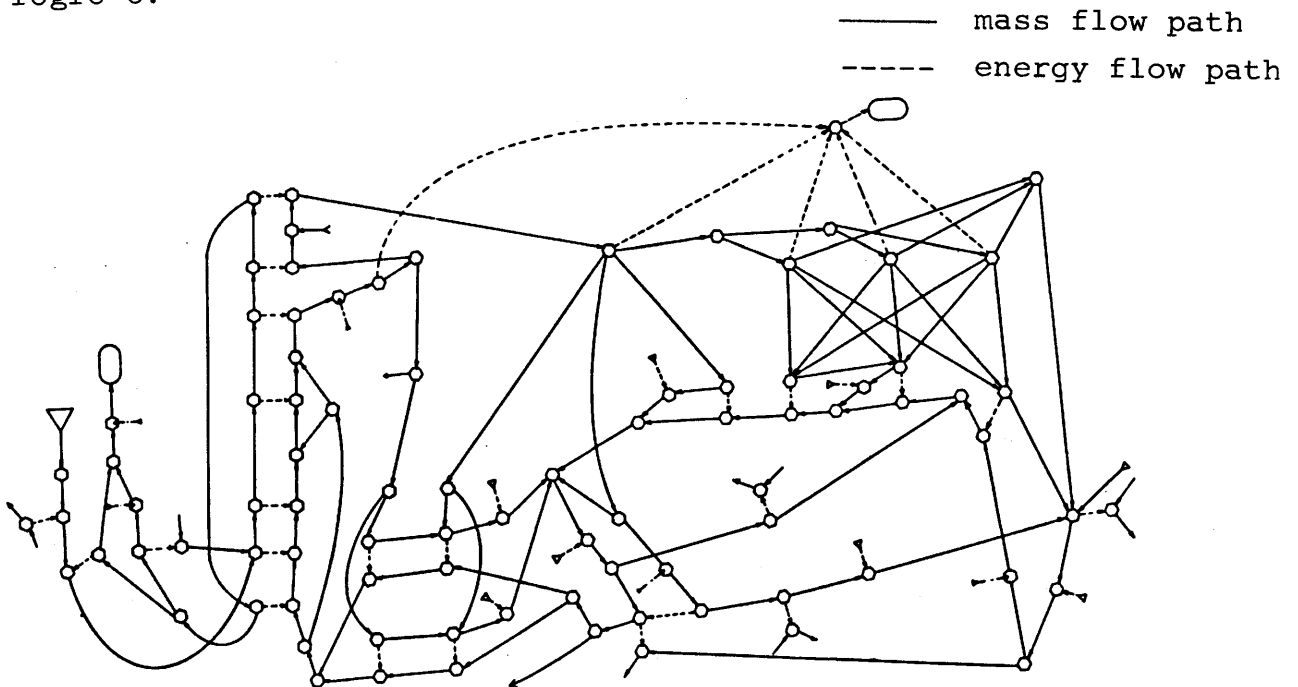
----- energy flow path

Fig. 21. Energy and mass flow model of fossile power plant, see
fig. - shows the flows determined by intended proper function.
For details, see Lind (1979).

The model at this level of overall system function can only be formed by considering a properly functioning system, since the parameters of its global function depend upon the proper functional state of all parts and upon the couplings to the environment, e.g., input signals, supply of energy, etc. This implies knowledge of the reasons behind system structure, since the reasons and purpose define proper function. Compare the role of the "principle of least work" in Hamiltonean theories.

The consideration of reason also influences the modelling process at lower levels of abstraction, but more implicitly. Since the elements of the models at these levels are familiar, generally used objects and functions, their existence as standardized elements per se reflects purpose and reason.

The transition from the domain of functional structure to that of abstract function is probably most evident when considering information processing systems. Here, the overall function of the system must clearly be described independently of the local physical functions of its elements, since the information content of physical variables and states depends purely upon a set of translation conventions.

Use of a model at the level of abstract function clearly depends on the definition of such a set of conventions to relate variables of a system to those of the model.

A model in terms of flow of energy, matter and information is a symbolic model, and its symbols are probably especially well suited for human data processing, since flows in a topographic map are well suited for imagery and visual processing. The distinction between natural language processing and the use of variables/relations is not very clear at this domain; a feature which defines phenomenological descriptions in general? The relation of this level of model to thermodynamic theories should be considered. Cassirer (1923) notes: "Whether we conceive energy as a substance, or as the expression of a causal relation, depends finally on our general idea of the nature of the scientific construction of concepts in general".
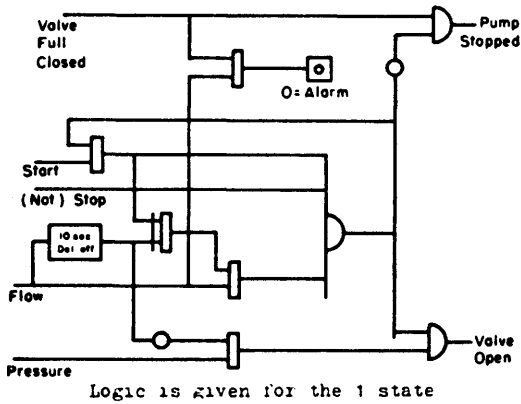
Figs. 22 and 23. Functional structure of a system represented by the functional effects upon the environment, i.e., abstract functional model in terms of events and states. Diagrams are from Wheeler (1975).
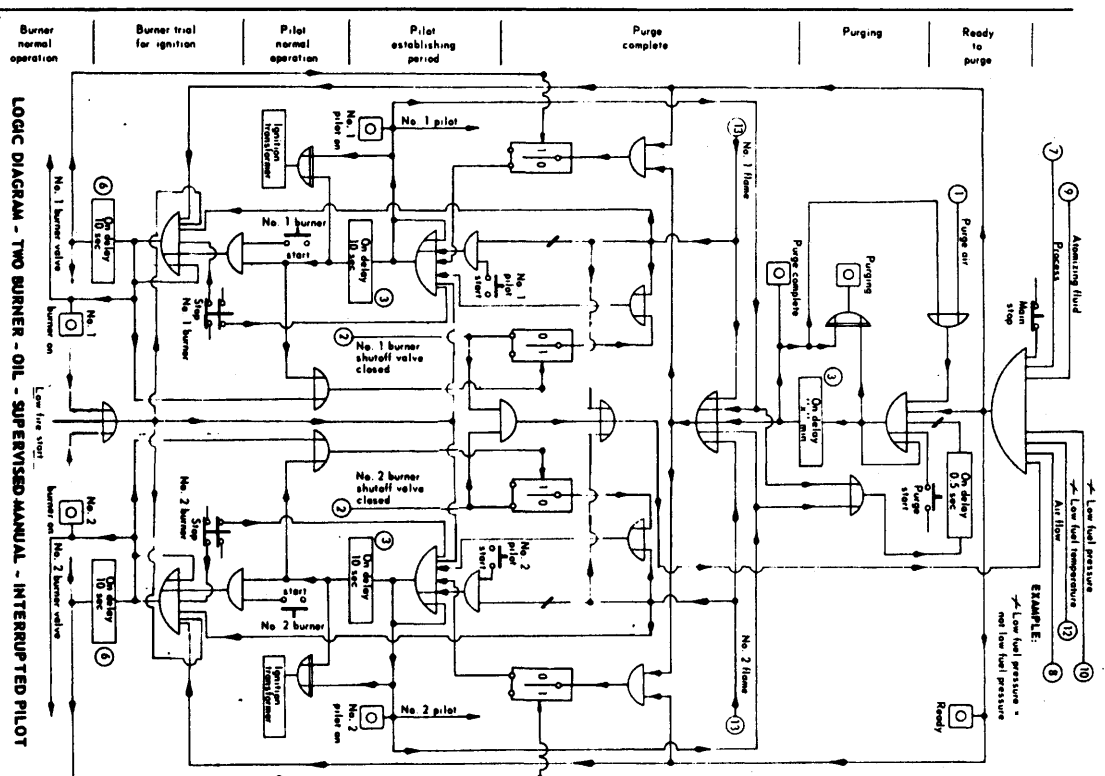
In the domain of natural sciences, this level includes theories derived from general principles which act as a kind of reason from which system properties can be deduced: First and second law of thermodynamics; "survival value" of Darwin's theory; "least work" of Hamilton's theory, etc. Psychological models in this domain are typically those of recent cognitive psychology which are based on formal information processing concepts and cybernetic principles. Technical examples are illustrated in figs. 20 and 21.

In data processing related to interaction with a physical world, this level of model can generally be used to structure the total system function - for the properly working system. This model therefore supplies references in general terms to judge performance of a system.

MODEL OF THE FUNCTIONAL MEANING OR PURPOSE

The definition of the system model was stated as a representation of the constraints upon the relationship among the variables which can be observed from a system. In the models discussed so far, the constraints have been related to the structure and properties of the system, even though the modelling to a large extent is controlled by consideration of the "purpose" of the system. It is, however, also possible to relate the constraints directly to the environment, i.e., to express the system model in terms referring to functional properties of the environment. This is, e.g., the case when the function of a control system is represented in terms of its effect upon the function of a connected process plant or when the function of a computer is represented by a decision table or a decision flow chart in terms of problem variables.

The model of functional meaning specifies the properties of a system in terms of relations between variables or states and events in the system's environment. Other specifications ex-

press desired states or magnitudes of variables directly or to
values of states and variables. Such specifications are state
models rather than functional models.

The concept of functional meaning has very close relation to the
definition of system boundaries. "Functional meaning" is a
concept representing the function of one part of the environment
in terms of the rest of the environment, i.e., it implies a
boundary around the "system", which will change with the at-
tention of the observer. The "system" is that part of the en-
vironment which the observer wants to control or influence, the
part between the potential actions or inputs and the observed
output.

Figs. 22 and 23 give examples of models in terms of the func-
tional meaning of industrial control systems.

The functional properties of systems with autonomous internal
organization originating from adaptive or learning capabilities
cannot be represented by straightforward information on the
internal anatomy or function. In this case it is generally pref-
erable to use models in the domain of functional meaning. This
is particularly true when models of man's decision making is
needed. Such "intentional models" (Dennett 1971) can be used to
predict system response from knowledge of the input information,
and the actual intention (or purpose) of the system (or the
designer), since it can be assumed that the system behaves
rationally as long as the actual performance does not surpass
the capability limits of the system. This kind of model is not
only used when dealing with self-organizing goal-oriented sys-
tems, but can also be used effectively to recollect degenerated
functional models of less complex systems. These models are then
obtained by "redesign" of the system based on assumption of the
design intentions or purpose combined with general professional
knowledge of the applied technology or internal functional
elements.

COPING WITH COMPLEXITY

In the verbal protocols we have evidence that the ability of man to cope with the complexity of industrial environments, is due to his ability to shift his internal representation or mental model freely and effectively to match the immediate task demands.

In the analysis of the behaviour of people working on technical systems, our modelling of his mental processes is performed in terms of information processing concepts. To avoid confusion with man's own mental models of his work environment, our models of his mental mechanisms will be termed <u>descriptions</u> in the following sections. This description will only deal with his cognitive functions. The psychological basis for these functions as well as the influence of affective functions and personal preferences and values are, of course, of importance. However, it will be a great advantage if the cognitive and affective functions can be described separately. Possibly then, concepts such as performance criteria, subjective goals, and "performance shaping factors" can be used to relate the concepts of data processing, used for functional descriptions, with the concepts of human values, used in descriptions of emotional states, see fig. 24.

The output of a human data processor in interaction with a physical system always consists of actions, i.e., changes of the spatial arrangements of things, i.e., the body and external objects. Actions have extensions in time, and decompositions of a current activity into a sequence of actions can be done in many ways. In the present discussion, we can define an action to be part of performance which follows as one integrated, smooth piece of behaviour, the conscious forming of an intention - to turn a switch, to make tea, to start a car. The size and complexity of actions then very reasonably depend on the skill of the individual man. This means that actions are the pieces of behaviour which are performed under control of the internal, dynamic world model without conscious control decisions.

Man as a system component. Design of systems depends on descriptions of man and machines which are compatible in structure and concepts. For automated systems, information processing concepts are natural choices for integrated functional design. Functional properties of man depend, however, on emotional features of work situation.

System as man's work environment. Consideration during design of subjective values and preferences demands a description of work situation in psychological terms, relating features of the situation to subjective values and emotional states.

Two separate descriptions are then needed for compatibility with engineering and psychology. Parameters and variables suitable for description of their interaction must be found. Descriptions of human mental functions typically depend on situation analysis and information process models. Descriptions of subjective values and preferences typically depend on factor and scaling analysis and emotional state models.
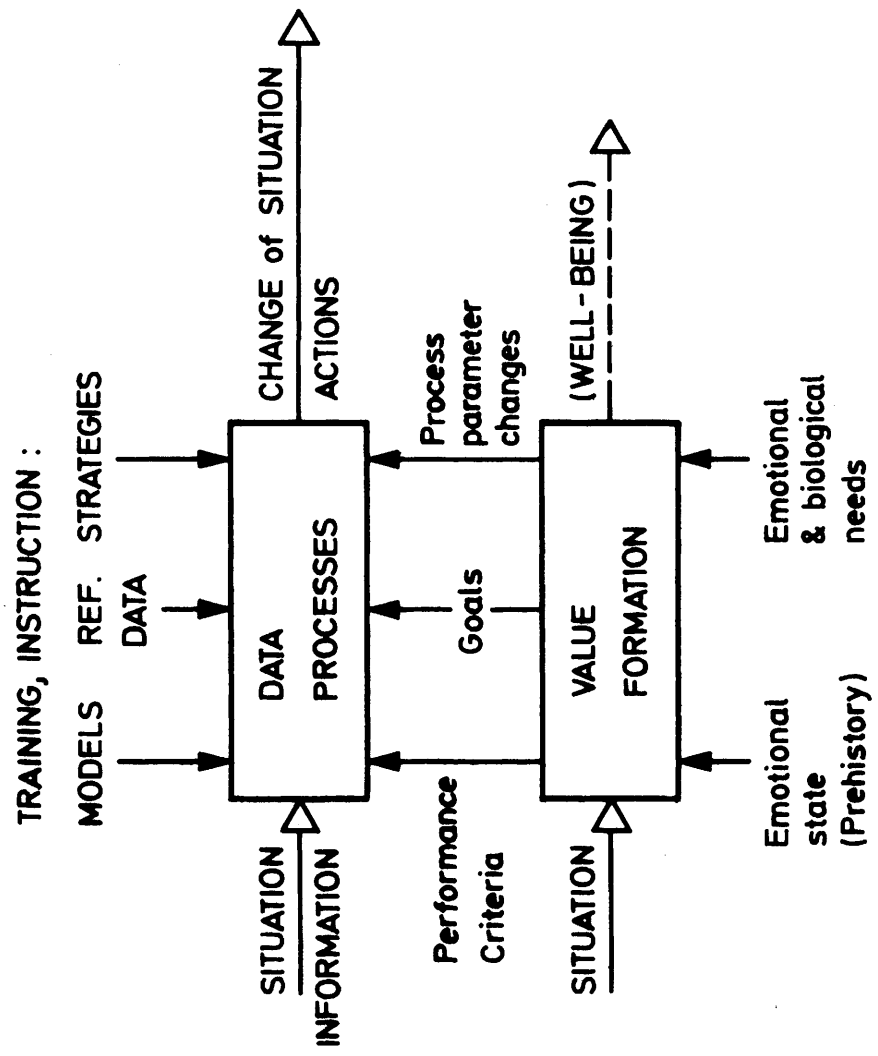

**Figure 24 Destriptions of related human functions & values.**

This is the first trick for coping with complexity: Temporal integration of the interaction of body and environment into behavioural units serving familiar intentions with transfer of control to the high capacity subconscious system; at level 1, fig. 25.

To cope with less familiar situations, a sequence of such actions must be controlled by a conscious linking together of a sequence of proper intentions which then can activate the related actions. In the following discussion, a sequence of intentions and actions designed to bring the environment into a specified state is called a procedure. Such a procedure generally contains a sequence of statements of system states separated by specification of actions which will bring the system into the next state. A procedure implicitly contains elements of a model of the physical function of the system in that it specifies the relation between events induced by human actions and the consequent state of the system, which is then related to the next action of the procedure. However, it is a very rudimentary model, linked to a restricted flow of events which are valid under special conditions and purposes.

The procedure used in a specific man-machine interaction can be based on a stored set of rules which are empirically collected during previous occasions and thereafter selected and stored as successful sequences; or they can be generated by some other person and prescribed in the form of work instructions. In both cases, we are in the domain of stereotyped, rule-controlled performance, level 2 of fig. 25. See also fig. 27 on page 44.

In new situations when appropriate procedures have not yet evolved or cannot be composed of familiar subsequences, the task must be accomplished by goal-controlled performance, i.e., the proper sequence must be selected from trial and error or based on causal functional mental operations.

Mental operations in this domain are depending on the functional models of the environment described in the previous section. Further, the mental processes must be controlled by a complex set of process rules which can be described in terms of a hierarchy of strategies. Like the different categories of
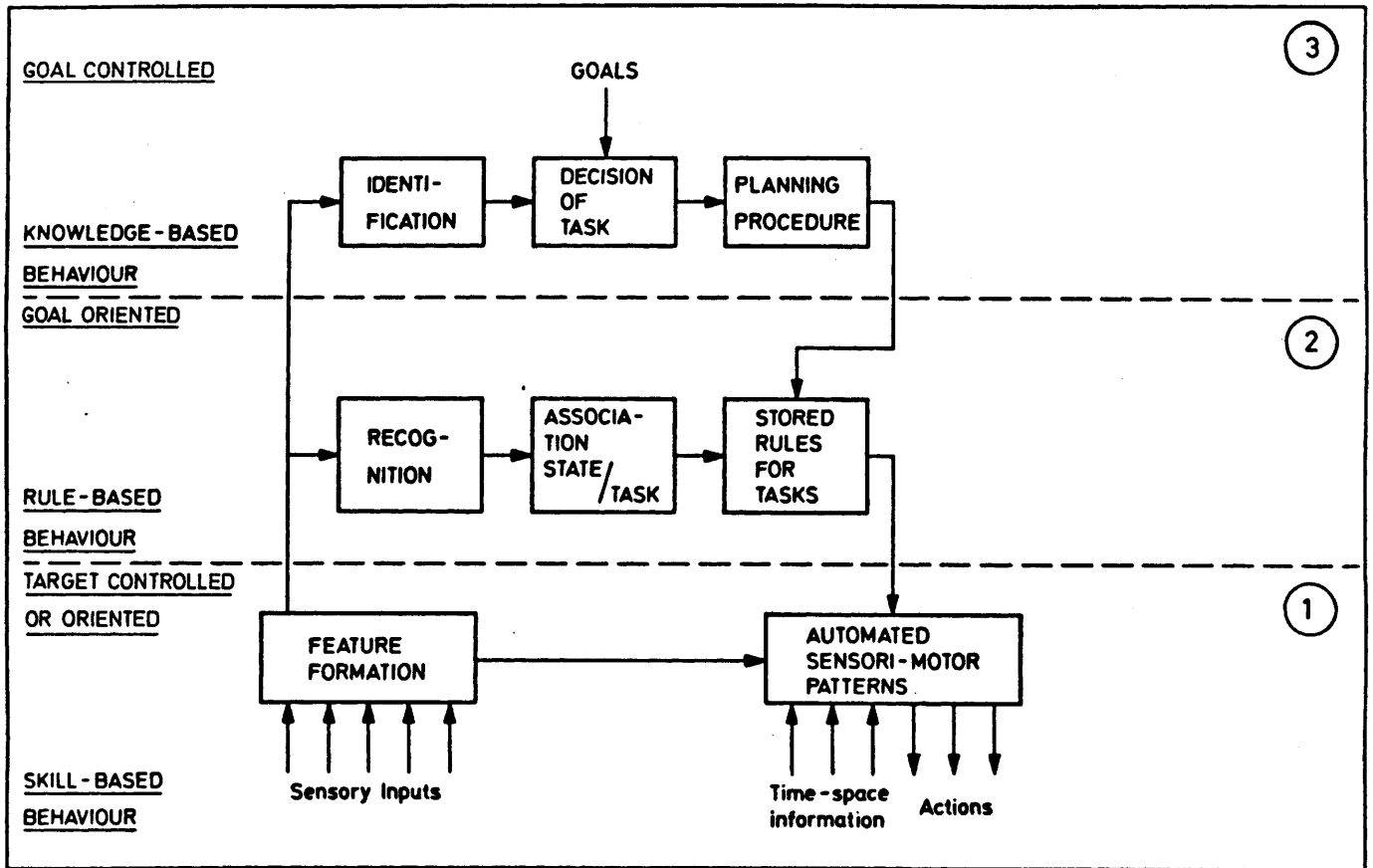
Typical descriptions of human data processing:

Level (3):   Heuristic problem solving strategies, artificial
              intelligence models.

Level (2):   Natural language models; decision tables; associ-
              ative nets; fuzzy sets.

Level (1):   Control theoretic models; bandwidth-gain-descrip-
              tions; sampling and queuing theory.

Fig. 25. Schematic illustration of different categories of
human data processing.

models, different categories of rules and strategies can be formulated; categories which are specifically tied to different types of environments, tasks, goals or subjective performance criteria. The efficiency of humans in coping with the complexity of the physical world is due to an ability to apply knowledge from previous experience to new situations by selecting and freely combining models, rules and strategies which have proven successful separately in other situations. In the present context, only the role of the different categories of functional models will be discussed in some detail.

Several problems meet the human data processor in the interaction with a complex physical environment. Only a few elements of a problem can be within the span of conscious attention simultaneously. This means that the complex net of causal relations of the environment must be treated in a chain of mental operations, often leading to effects like the law of least resistance and the point of no return. That is, strategies which depend on sequences of simple operations are intuitively preferred, and there will be little tendency to pause in a line of reasoning to backtrack and develop alternative or parallel paths (Rasmussen 1974).

An effective way to counteract limitations with processor capacity and short term memory seems to be to modify the basis of mental data processing - the mental model - to fit it to the specific task in a way which optimizes the transfer of previous results and minimizes the need for new information. The efficiency of human cognitive processes seems to depend upon an extensive use of model transformations together with a simultaneous updating of the mental models in all categories with new input information, an updating which is performed below the level of conscious attention and control.

Several strategies for model transformation are possible and are generally used to facilitate mental data processing, such as:

- Aggregation; elements of a representation are aggregated into larger units, chunks, within the same model category as familiarity with the context increases.

- <u>Abstraction</u>; the representation of the properties of a system or the environment in general is transferred to a model category at a higher level of abstraction.

- <u>Use of ready-made solutions</u>; the representation is transferred to a category of model for which a solution is already known or rules are available to generate the solution.

Hierarchical Aggregation

For this strategy, elements of a model are aggregated into larger units at the same level of abstraction. At the level of physical function for instance, objects are lumped into larger physical objects and thus a hierarchical structure of parts and wholes is formed. Typically, a number of frequently found objects are united into more specialized objects. In man-made systems, identification of objects or components is structured according to their purpose, and it is, therefore, the purpose of a physical system which has a hierarchical nature rather than the system itself. This illustrates the point that models at each level of abstraction depend both upon the physical realities as well as upon the purpose or the functional meaning of the system. Thus the physical world supplies <u>potentialities</u>, in the form of possible functions while purpose or functional meaning selects the <u>actualities</u>, the realized functions.

This kind of hierarchical decomposition of the purpose or functional meaning can be performed within each of the categories of models.

Abstraction

The different levels of abstraction formed by the categories of functional models discussed in the present report are created by selecting potential functional properties of the physical world and then expressing them in purposive structure at different levels of abstraction. At the lowest level of abstraction, the model and its elements are tied to a specific physical system or

type of system, but can represent the properties of the system under varying functional conditions or for different purposes. The model can be conveniently modified according to changes in the physical world, for instance to take into account the effects of spontaneous changes in the material structure, "faults".

On the other hand, at high levels of abstraction, the models are more closely related to a specific actual purpose, to the intended functional properties and to a large extent they are independent of the physical world underlying the function.

In other words, models at low levels of abstraction are related to a specific physical world which can serve several purposes. Models at higher levels of abstraction are closely related to a specific purpose which can be met by several physical arrangements. Therefore shifts in the level of abstraction can change the direction of potential paths for transfer of knowledge from previous cases and problems. At the two extreme levels of models, the directions of the paths available are in a way orthogonals, since transfer at one level follows physical, material properties, at the other it follows purpose.

Important human functions in man-machine systems are related to correction of the effects of errors and faults. Events can only be defined as errors or faults with reference to intended state, normal function or other variants of system purpose or functional meaning. The functional models at the different levels of abstraction play different roles in coping with error struck systems. Causes of improper functions are depending upon changes in the physical or material world, they are explained "bottom--up" in the levels of abstraction, whereas reasons for proper function are derived "top-down" from the functional meaning, see fig. 26.

The clear distinction between causes of faults and reasons for function has been discussed in detail by Polanyi (1958): "There is a specific reason for every step of a procedure and every part of the machine, as well as for the way the several steps and various parts are linked together to serve their joint pur-

MODEL CATEGORY	STRUCTURE	ELEMENTS	RELATIONS	DATA	ASPECTS OF MATERIAL REALITY IN THE SYSTEM	ASPECTS OF SYSTEM PURPOSE
FUNCTIONAL MEANING	Related to properties of environment	Physical variables, processes or objects of environment	As required by system's environment	Magnitude of variables or states of objects, processes	If present, only preserved in terms of limiting properties and assumption of rationality	Models expresses largely the requirements of the environment
ABSTRACT FUNCTION	Topology of overall causal structure of system	Abstract variables related to state in causal net	General laws, conservation laws; logic relations	Symbolic, quantitative variables; truth values; related to modelling language	Only causal structure preserved	Operating state of system with respect to purpose defines causal structure
FUNCTIONAL STRUCTURE	Network of relations ordered in sets, i.e., typical functions	Physical variables	Sets of physical laws and empirical relations; equations, graphs, tables related to typical functions and processes	Magnitude of variables	Physical processes and variables are represented	Typical elements of system purpose specify physical processes and functions
	Set of "objectivized" typical functions	Typical processes or functions	Potential for interaction between processes and functions	States of functions; events		
PHYSICAL FUNCTION	Sets of variables related to typical objects	Physical variables	Input/output relations of typical components, equations, graphs, tables	Magnitude of physical variables	Physical objects and related physical variables are represented	Typical elements of system purpose determine level of object formation and relevant variables or properties
	Set of interacting objects or components	Typical components	Potential for interaction between objects	States of objects; events	Physical objects and their qualitative properties are represented	
PHYSICAL FORM	Lumped topographic map: "landscape of typical objects"	Objects, technical components	Spatial distance	Form and spatial position of objects	Physical, material objects and their spatial relation	Elements of overall purpose determine object formation
	Distributed spatial maps	Fields of uniform surface or matter	Spatial arrangement	Location of fields of sense data; visual, tactile, auditive	Portrait like map of material landscape	Purpose determines mode and resolution of recording senses

PURPOSE BASE - REASONS

MATERIAL BASE - CAUSES

Fig. 26. Morphology of functional models.

pose". ---- "Since rules of rightness cannot account for fail-
ures, and reasons for doing something can only be given within
the context of rules of rightness, it follows that there can be
no reasons (in this sense) for a failure. It is best therefore,
to avoid the use of the word "reason" in this context and to
describe the origins of failures invariably as their causes".

Another human task for which the use of representations at sev-
eral levels of abstraction is of obvious value is the design
of technical systems. Basically, system design is a process of
iteration between considerations at the various levels rather
than an orderly transformation from a description of purpose to
a description of the concept in terms of physical form. There
exists a many to many mapping between the two levels, a purpose
can be served by many physical configurations and a physical
system can serve many purposes or have a variety of effects.

The use of different categories of model in a design strategy
has been explicitly discussed by Alexander (1964, p. 89): "Every
form can be described in two ways: from the point of view of
what it is, and from the point of view of what it does. What it
is is sometimes called the formal description. What it does,
when put in contact with other things, is sometimes called the
functional description". Alexander continues (p. 90): "The
solution of a design problem is really only another effort to
find a unified description. The search for realization through
constructive diagrams is an effort to understand the required
form so fully that there is no longer a rift between its
functional specification and the shape it takes".

If we accept the complex of strata between physical form and
functional meaning of technical systems, an "invention" is re-
lated to a jump of insight which happens when one mental struc-
ture upward from physical form and another downward from func-
tional meaning, which have previously been totally unconnected,
suddenly merge to "a unified description".

The number and characteristics of the categories of functional
models discussed in the previous section have been derived from
considerations connected with electronic data processing systems

OPERATORS' INFORMATION BASE

BEHAVIOUR	REFERENCE DATA STATE PATTERN MODELS	STRUCTURED AND RELATIONS FUNCTIONAL MODELS	PROCESS RULES STRATEGIES AND PROCEDURES
GOAL CONTROLLED, KNOWLEDGE BASED	Goals and targets. Performance criteria. Political, business criteria.	Value structures. Relations among goals, values. Structure and operation of goal setting organisation.	Mental strategies and heuristic rules for conscious processes: - Deduction, abduction and search. - Explanation, prediction, evaluation. - Planning - i.e. mental experiments, selection and storage of procedure. - Manipulation of symbols; mathematical, graphic. Schematics and drawings. Elements of strategies - the process rules - are system and task independent but model specific.
	Set points and reference value figures. Test and calibration figures and patterns.	Functional meaning. Purpose of functions; control system objectives, purpose of safety systems and interlocks. Objectives of auxiliary systems.	
	Physical/symbolic translation constants, truth tables, etc.	Symbolic function. Energy, mass, information flow causality. Logic functions of control and safety systems.	
	Normal and limiting figures material and process parameters and constants.	Functional structure. Variables and their relations. Water/steam tables, heat transfer laws, neutron physics relations.	
	Normal operational states, fault states.	Functional structure. Properties of standard functions, their interaction. Criticality, boiling, cooling, water treatment, feedback loops.	
	Normal operation figures. Limiting value figures.	Physical function. Variables and their relations, physical characteristics in graphical plots and numerical laws.	
	Normal states, fault patterns.	Physical function. Properties of parts and components. How components work. How they are connected and interact.	
	Names and labels of things, components, places.	Physical form. Physical appearance of parts, components, switches, keys and indicators and their locations. Anatomical and topographical maps.	
GOAL ORIENTED, RULE BASED	State pattern models, references for recognition and identification of states, events, situations, etc.	Associative net relating states, events, situations, needs to tasks or activities. From instruction or experience (or derived by functional reasoning).	Procedures - rules for sequence of actions upon the physical system or environment in general. Task and system specific: - Administrative - legal instructions. - Technical work procedures. Prescribed by instruction - verbal or written - or stored from previous successful occasions, or generated from functional knowledge.
MODEL CONTROLLED, SKILL BASED	Templates for activation of reflexive performance by events, objects, situations. "Process-feel".	Subconscious model of physical "landscape". Dynamic world model; schemata for control of bodily and manual activities: Locate, orient attention and body. Move around, manipulate tools, equipment, symbolic aids.	Not relevant

(diagonal label within table: PURPOSE BASE, REASONS / PHYSICAL BASE, REASONS)

Fig. 27. Schematic map of operators' information base.

for which all of the levels are found to be of importance for human reasoning. This is not necessarily the case for other types of systems since the functional meaning may be directly related to the lower levels of abstraction, consider for instance transportation and manufacturing systems. Only for information systems, where flows of energy and matter have no direct relevance for the ultimate purpose but are purely means to obtain a causal connection between events or variables which are otherwise unrelated, is the functional purpose directly related to the level of abstract function.

Transfer of Results and Rules

Each level of abstraction or category of model depends upon a special model language, i.e., a set of symbols and syntactic rules. Shifting the level of modelling can be very effective in a problem situation since data processing at another level can be more convenient, the process rules can be simpler or better known or results can be available from previous cases. A special instance of this strategy is the solution of a problem by simple analogy which depends upon the condition that different physical systems have the same representation at higher levels of abstraction.

In some cases, efficient strategies can be found where symbols are transferred to another level of abstraction and reinterpreted. A simple example will be the subconscious manipulation of symbols which are reinterpreted as artificial objects, e.g., Smith's (1976) solution of scheduling problems by manipulation of rectangles; or the reinterpretation of numbers in terms of actions for calculations by means of an abacus.

This recursive use of the categories of functional models adds another dimension to the variety of tricks to cope with complexity. The most general and effective is, of course, the use of natural language to represent the models verbally at all levels of abstraction. However, this generality is offset by the difficulty of keeping track of the context, i.e., the category of model behind the symbols.

CONCLUSION

As the preface has indicated, the scope of the present report has been to discuss a taxonomy of models in task independent terms.

In the present form the discussion of different types of models appears somewhat pedantic, because their complex interaction in real human data processing cannot be described unless the large repertoire of strategies which are used is also treated. The strategies and the frequent jumps between strategies in particular depend very much upon the actual task and the specific work situation and cannot be discussed in general terms. The interaction between strategies and models has been discussed in some detail for a diagnostic task elsewhere (Rasmussen, 1978) and will be the subject for further study.

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Abstract

The report is a working paper which describes and illustrates different forms of mental representations of the functional properties of a physical system as found in a man-machine system context.

The outlines of a morphology of such models are discussed in terms of different levels of abstraction related to physical form; physical function; functional structure; abstract function; and functional meaning or purpose. The distinction between deterministic quantitative models based on variables and relations, and causal, qualitative models based on objects or functions which have properties and interact by events, is discussed. The dependency of the different levels of abstraction upon representation of aspects of the material basis of the system versus aspects of human reasons for the existence of the system is described. Finally, the different strategies of humans to cope with complexity is briefly discussed in the context of the morphology.

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