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MODELING IN THE CONTEXT OF COMPUTER SCIENCE – A METHODOLOGICAL APPROACH

1. Introductory remarks

Modeling is one of the basic methods in *empirical* sciences. Generally speaking, it consists of the gradual construction of a cognitively useful – though simplified and idealized – image of described phenomena. As this image often takes the form of an abstract **formal description** – for example, a system of equations, or a set of logical formulas – modeling relies significantly on formal sciences such as mathematics, logic, or computer science.[1]

The following can be pointed to as typical **examples** of models constructed in empirical sciences: a) in physics – models of the *atom*, for example, the Bohr atomic model; b) in neurobiology – models of the *neuron*, for example, the McCulloch-Pitts linear neural model [McCulloch, Pitts 1943]; c) in psychology – computerized models of semantic memory, for example, Quillian's network model [Quillian 1968]; d) in cognitive science – partial[2] models of *mind*, including a rich collection of rule-based reasoning models (implemented in the form of expert systems) [Stacewicz 2010].

[1] In formal sciences, especially in logic, models are also discussed in different terms. This is especially so in the case of semantic (logical) models [Marciszewski 1998; *Mała encyklopedia logiki*; entry: *model semantyczny* (*semantic model*)]. These are interpretations of axiomatic systems which make their axioms true (thus making true all statements derived from these axioms). It must be provisionally noted that a fragment of a theory which has a semantic model, that is, an interpreted theory, may play the role of a theoretical model of a given object (a model as an image – in the sense mentioned above.)

[2] The expression *partial model* means that a given model concerns a certain section of mental activity, for example, particular cognitive functions, such as learning or reasoning.

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The last two examples demonstrate that many – if not most – contemporary models have the status of **computer science models**, that is, formal constructions which are described theoretically in the language of computer science (the language of algorithms and data structures), and, therefore, can be implemented in the form of applications and activated on a computer.

As modeling is a cognitive procedure – carried out primarily in empirical sciences, but significantly involving the theoretical means of formal sciences – both this procedure and the generated models are the object of **methodological analyses**, that is, analyses pertaining to the methodology of sciences, both empirical and formal. For this reason, the relationships between the model and the theory, as well as the model and the metaphor reconstructed below will be called ***methodological relationships***.

In this article we will concentrate on the **methodology of computer science**. This means that we will discuss computer science models. However, the models which will be discussed are used for the description of phenomena whose nature is different from data processing in artificial systems.

The above mentioned methodological relationships may be studied by taking a **dynamic** approach – that is, in the context of modeling activity, as well as by taking a **static** approach – that is, in the context of temporary products of the modeling process.

In the first mentioned context above, it is necessary to take into consideration the compound modeling procedure which, as we will see, has a **cyclical**, **open** character and involves various operations connected with the formalization, interpretation, simplification and verification of subsequent versions of the model being constructed. The procedure is often initiated by a metaphor which determines the rough shape of future models.

To conclude these introductory remarks we must mention that the most significant function of a model in the methodological sense is **mediation** between the researcher and the studied object (the phenomenon). This means that a model leads to the discovery of new knowledge about the studied object. Specifically, it allows for certain problems pertaining to the object to be perceived and formulated, and then for an attempt to be made at addressing them. The mediatory function understood in this way is necessary in two situations: firstly, when the studied object is cognitively inaccessible (for example, for technical or axiological reasons), secondly, when the studied object is too complex to be studied directly and totally (as happens, for instance, in the case of the human brain).[3]

[3] The mediatory function which characterizes models makes the tripartite system

2. Computer science models

Generally speaking, models (in the methodological sense) can be divided into **theoretical** and **real** [Marciszewski, 1988; *Mała encyklopedia logiki*; entry: *model*]. The former consist of a set of simplifying assumptions[4] and theses which can be derived from them, while the latter are physical *realizations* of adopted assumptions and theses; i.e. objects and systems of objects which satisfy them. The aforementioned assumptions and theses constitute the theoretical image of the studied object and they derive from the theory according to which (or parallel to which) the model is built. Therefore, the theoretical model should be treated as a certain narrow fragment of the theory whose aim is to specify the description of a limited group of phenomena and to solve problems concerning this particular group. Most often these are phenomena of one type only, for example, human cognitive processes.

Due to its pertinence to a particular theory, the theoretical model performs cognitive functions similar to a theory: it allows for the formulation of hypotheses, its adequacy may be tested, it enables problem solving and it provides the necessary explanations. It is highly important to bear in mind, however, that the model and the theory are constructed in a parallel way – that is, the theory is not closed and definite: the theory changes in the course of the verification of the model and its development among others.

In fact, when discussing the theory entangled in the modeling procedure, one has to consider two theories: a) the first is the **meta-theory** – the formal theory which provides (not yet interpreted) language for the model; e.g. in the case of the linear model of a neuron, it is the simple matrix algebra (see subsequent example); b) the second, however, is the **proper theory**, that is, the theory of the discipline being studied which is formulated and, at the same time, formalized in the language of the meta-theory. The proper theory is, therefore, the very basis for the construction of the model, while

[*researcher-model-reality*] the natural context for their analysis. In this system the researcher plays the decisive role, as the subsequent steps of modeling procedure depend on his decision. However, is the researcher's presence necessary at every step of modeling? Can this procedure not be automated? These are important questions which today – in the age of computer models and ever more autonomous computer systems – take on real meaning.

[4] Choosing particular assumptions, one decides which features of the studied object are cognitively significant, and, furthermore, "effective" as far as the aim of the research is concerned.

the meta-theory (or strictly speaking, its fragment) may be called the formal basis of the model.

It should be added here that the concept of meta-theory is extremely flexible and that in the case of most advanced models more than one formal theory (for example, a particular field of mathematics) is considered. In other words, the meta-theory usually consists of a class of formal theories. For example – and this will be elaborated subsequently – the computer science models we are interested in here refer both to certain mathematical formalisms (for example, algebra) and to certain general methods or computer techniques (for example, genetic algorithms).

Although not all theoretical models must be formalized – some of them may take the form of precise verbal descriptions – **formalized models** are considered to be the most advanced. These are formal constructions interpreted in a particular subject domain. They are defined in the language of mathematics or disciplines which are closely related to it, such as logic or computer science.

Depending on the discipline from which the formal frame of a model is derived, models are therefore qualified as mathematical, logical, computer scientific, etc. It must be borne in mind, however, that each of these disciplines has its particular divisions which allows for the use of narrower terms such as, for example, algebraic models.

2.1. Models Formalized Using the Language of Computer Science

An extremely useful – and due to the speedy development of computer techniques, nowadays dominant – class of formalized models are **computer science models** (CSMd). These are constructions formalized in the language of computer science which usually rely on certain techniques/methods of data processing. They are carried out in practice by means of computer programs or programmatically controlled systems. Such constructions are frequently used for the description of very complex phenomena evolving with time, for example, mental processes.[5]

The following are typical **examples** of CSMd in the field of mental phenomena: **a)** models of **reasoning** – referring to logic and realized, for example, within a framework of rule-based expert systems; **b)** models of **perception** – referring to neurobiology and often proposed in the form

[5] This includes both the general language of computer science (concerning certain typical structures of data and the rules of processing them) and a particular language connected with a certain distinct "micro-theory" of data processing (for example, rule processing within the framework of specified expert systems).

of artificial neural networks; **c)** models of **learning** – referring to psychology and realized by means of systems able to increase their effectiveness depending on their interaction with the environment[6] [Russel, Norvig 1994].

With regard to the computer science models presented above, the concepts of the theoretical model, the real model and the formal basis of a model take shape.

In this case:

a) the **formal basis** of a model is: **a1)** in a broad sense – a certain distinct theory of data processing: for example, a theory of data processing by (generally speaking) artificial neural networks; **a2)** narrowly understood – a certain algorithm,or a set of algorithms which specifies in an abstract manner particular methods of data processing, described generally by the **a1** theory (for example, perceptron type networks learning through backward propagation of error information); **b)** an application[7] is **a theoretical model**: an algorithm coded in a particular programming language and applied in a particular interpreted field; **c)** a **real model** is – **c1)** a *running* (activated) application, the subsequent steps of which can be traced (for example, on the computer display); or **c2)** a *running system*, controlled by the application which, contrary to the application itself, directly interacts with the environment. In the case of **c1** we are dealing with a *virtual* real model, while in the case of **c2** it is a *non-virtual* real model.

Regardless of the aforementioned realizations, it should be noted that CSMd is rarely a purely **computer science model**. More technically speaking, its meta-theory rarely pertains to computer science only. By that we mean that most CSMd have a certain mathematical (for example, algebraic) description which is more primitive and superior with respect to

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[6] Even the examples provided suggest that a model is named *computer science model* for the reason of the modeling method which is itself connected with computer science, not because of any other elements, such as the object of modeling, the source of observational data or the source of inspiration for research (although these elements may also derive from computer science).

[7] We do not use the concept of the computer program here (replacing it with the concept of application), because in theoretical computer science this concept merges with the concept of algorithm. This is mainly because most algorithms are presented in the form of programs written in the high level languages of programming (for example, in PASCAL). The term application is better suited here, because it draws attention to the fact of the use (application) of an algorithm in a particular field. We could say therefore that applications are interpreted programs/algorithms.They are interpreted because they are put to a particular use.

computer science. This is realized and often expanded by means of computer science concepts (for example, by the introduction of specific data structures). In other words: such models have a **deep** (mathematical) layer and a **proper** (*sensu stricto* computational)[8] layer.

Preempting slightly the contents of Chapter 4 in which we will undertake an analysis of modeling procedure, we must affirm that, as far as computer science models are concerned, modeling involves various activities, amongst which **programming** (creation of applications) is considered to be central. Apart from programming, we should also mention **algorithm design** (or use of the existing algorithms) on the one hand because it precedes programming and is more general in character, and on the other hand the **formalizing** of phenomena and processes in the language of mathematics.The latter is even more primitive and it determines the shape of an algorithm and its respective application.

2.2. Examples of Computer Science Models

The above mentioned distinctions and explanations will be illustrated with a well-known example of the **model of a neuron**, initially proposed by McCulloch and Pitts [McCulloch, Pitts 1943] which, at present, is developed in many different ways within the theory of artificial neural networks (cf. for example [Tadeusiewicz 1993], [Żurada 1992]).

The theoretical basis for the primary model and its various developments is formed by the following *simplifying assumptions*. Firstly, the model describes the regularities of the functioning of a neuron, not its biological properties, and therefore, its character is functional, not substantial. Secondly, three functions are considered basic for a neuron: the reception of impulses from other neurons, transforming these impulses into output signal and transferring this output to other neurons. Thirdly, the impulses received and transferred are coded numerically and the operations performed on them are notated in the language of mathematics – thus the model is formalized (mathematized) in character.

These general assumptions allow for many different theoretical constructions, among which the simplest (and historically the first) is the so-called <u>linear model</u>, formalized in the language of simple algebra. According to this model, a neuron consists of: a) n inputs of definite weights (these in-

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[8] As both theoretical computer science and mathematics are formal sciences, and the scope of their competences often converge (thus often giving rise to the problem of the vagueness of their scope), the difference between the mathematical layer and the computer science layer of a model is not always easy to discern.

puts correspond to real dendrites), b) one output (corresponding to the real axon) and c) a processor transforming the input signals. As far as the functioning of a neuron modeled in this way is concerned, it is assumed that the neuron consists of the reception of n input signals (from x_1 to x_n) of values ranging between [0,1], transforming them into the output signal following the (algebraic) formula $y = \Sigma w_i * x_i$ (where w_i is the weight of the i-input), and transmitting the signal to other neurons. Because of the type of function being used to consolidate the input signals x_i (the weighted sum), the model is called a *linear* one. By choosing other functions – allowed by the initial assumptions – other models are generated (see, for instance, [Tadeusiewicz 1993]).

The description mentioned here characterizes the theoretical model formalized in the language of mathematics (simple algebra) and, therefore, it is a mathematical model. If this model were developed in the form of a running application simulating both the functioning and – having extended the model – the learning faculty of a real neuron, a theoretical computer science model would be created. If the application were run on a computer, or if an electronic system corresponding to it were constructed, we would be dealing with a real computer science model.

The issues surrounding models, characterized above, become most apparent when the linear neuron model becomes the basis for a wider construction, i.e. a *linear neuron-like network* which is no longer a model of a single neural cell, but that of a certain brain region. In the case of this new model there is an actual need for reference to computer science theories (namely, the theories of artificial neural networks), as well as to some universal algorithms of functioning and learning of a particular kind of network. These theories should be treated as meta-theories, the algorithms as the least complex elements of the meta-theories, the applications created on the basis of them (and interpreted as tools for modeling neurobiological phenomena) as theoretical models, the running application models as virtual real models, and the physical systems controlled by these applications as non-virtual real models.

The second model we chose as an example refers to another aspect of computer science – not connectionist this time but a logistical one. The proposed construction is embedded in a particular situational context. This context should be regarded as a set of simplifying assumptions determining the shape of the model.

The context is a natural science experiment, the object of which is a rat trying to discover and record in memory the rules linking the appearance of particular external stimuli with the possibility of satisfying hunger and avoiding pain. The experiment consists of several repetitions of the same procedure: after emitting three signals – a light one, a sound one and a thermal one – the rat is to choose one of three containers. A bijective connection is assumed between the combination of the signals and the content of a container (with or without food) and the pain stimulus (present or absent).

The model concerns the **rat's memory** which is to provide the animal with the ability to differentiate, on the basis of a limited number of random choices, the stimuli leading to the right decision from all the others [Bolc, Cytowski, Stacewicz 1996]. The decision is considered right if the container with food is chosen, but only provided that the administration of food is not accompanied by pain. The model proposed has its **structural** part – determining the shape of memory – that is, the manner of representation of data linking the stimuli to possible reactions, as well as its **procedural** part – responsible for the use and alteration of the shape of memory – that is, learning.

The formal basis of both these elements of the model forms Zdzisław Pawlak's decision logic [Pawlak 1991]. Without undertaking a detailed reconstruction of the logical calculus, we will attempt to present the general idea of our model. Its structural part consists of attributes and their values, corresponding to the experimental situation assumed. These are as follows:

a – *number of the container*, with values 1, 2 and 3
b – *sound*, with values 0 (*weak sound signal*) and 1 (*strong sound signal*)
c – *light*, with values 0 (*weak light signal*) and 1 (*strong light signal*)
d – *temperature*, of values 0 (*cold*) and 1 (*hot*)
e – *food*, with values 0 (*absent*) and 1 (*present*)
f – *pain*, with values 0 (*none*) and 1 (*strong*)

The first four attributes (*a* to *d*) are called *conditional attributes* (their values are stimuli), the two remaining attributes (*e* and *f*) are called *decision attributes* (their values are the circumstances accompanying the stimuli). Using this kind of designation, it is possible to present the course of the experiment and the "raw" information coded in the rat memory modeled here in the form of the so-called *decision table.* Its successive rows contain information about the consecutive attempts made by the rat, i.e. the information on values of decision attributes which accompanied a given combination of conditional attributes. For instance, the third row of the table will be interpreted as follows: *"In the experiment, with weak sound and light signals, as well as high temperature (hot), in the container number 2 there was no food and the pain stimulus was non-existent."*

	a	**b**	**c**	**d**	**e**	**f**
1	1	1	1	1	0	0
2	2	0	0	0	0	0
3	2	0	0	1	0	0
4	2	1	1	0	0	1
5	2	1	1	1	1	1
6	2	1	1	1	1	1
7	3	0	0	0	0	0
8	3	1	1	0	0	0
9	3	1	0	1	1	0
10	3	1	1	0	0	0
11	3	0	1	1	0	0
12	3	1	0	1	1	0

The table above may be rewritten using a logical form, namely the form of decision rules R_i. Each R_i rule corresponds to the i-th row of the table. The a_v term in R_i rule means that in the i-th row of the table, v is the value of the a attribute. All a_v terms are linked by the conjunction symbol and the link between the condition attributes and decision attributes is marked by the implication symbol. For example, the first two rows of the table correspond to the following rules (the total number of rules is 12):

$$(a_1 \wedge b_1 \wedge c_1 \wedge d_1) \rightarrow (e_0 \wedge f_0)$$

$$(a_2 \wedge b_0 \wedge c_0 \wedge d_0) \rightarrow (e_0 \wedge f_0)$$

The notation above defines the structural part of the model, i.e. the formal way of representing the knowledge stored in the rat's memory. It may be generally assumed that knowledge of this kind forms a representative description of situations which may occur.

The functional element of the model has an algorithmic character and defines the way in which current knowledge is used, including its effective transformation. This element is necessary because, as we all know, the rat is intelligent, and thus it is able not only to preserve knowledge, but also to extract from it what is most crucial as far as the quality of the decisions taken is concerned. In other words, it can be assumed that the rat can perform an **effective reduction** of knowledge: firstly it can choose that part of it which is comparatively small, and, secondly, this provides the rat with the same decision making ability as full knowledge.

Wishing to model the assumed ability of the rat, one can rely on the method of decision **table reduction** elaborated by Z. Pawlak. It is one of the methods of learning using induction by elimination [Pawlak 1991]. Avoiding detailed description – noting, however, that there exists an algorithm of the method and that it is effectively being used – the following result of reduction can be given for the rules presented above:

$$
\begin{aligned}
&a_1 \lor b_0 \lor (a_3 \land d_0) &&\rightarrow e_0 \land f_0 \\
&a_2 \land b_1 \land d_0 &&\rightarrow e_0 \land f_1 \\
&a_3 \land b_1 \land d_1 &&\rightarrow e_1 \land f_0 \\
&a_2 \land b_1 \land d_1 &&\rightarrow e_1 \land f_1
\end{aligned}
$$

3. Computer science metaphor

The relationships between the model (generally understood) and the metaphor have a **generative** character. That is, there are models which derive from metaphors – metaphors understood as initial, **informal images** of the studied phenomena [Pelc 2000]. The model generation function of the metaphor is most clearly revealed in the case of phenomena/processes about which there are certain *imaginations* established in culture, although these may be vague. Such is the situation in the case of modeling mental functions. As typical examples of metaphors initiating modeling in this field, the following may be indicated: a) the mind as a *black box* (behaviorist psychology), b) the mind as a *brain* (neurosciences), and c) the mind as a *mechanism* (cognitive psychology, cognitive science). (see, for instance, [Stacewicz 2010])

A specific case of a mechanistic metaphor (point c) is the **computer science metaphor** (CSMt) which consists of comparing the modeled object (for instance, the mind) to an information processing system. In order to define it precisely – as will be explained further – one has to determine the type of information processing system and then reach for the theory describing how data is processed by such a system.

3.1. From Metaphor to Model

Contrary to the model, the metaphor which leads to the construction of the model has a general and imprecise character. It relies on the **initial comparison** of an object X to a better known and theoretically better described object Y. This comparison suggests a further possibility of describing object X by means of precise concepts concerning object Y. It includes also the possibility of heuresis, that is, the possibility of gaining new knowledge about object X. In order for these contingencies to take place, heuristically justified *similarities* have to occur between both objects, for example, structural or functional ones [Old, Priss 2001], [Stacewicz 2010].

We must add here that as metaphor is not a strictly scientific construction (only the model can become such), its **heuristic justifiability** is determined not only by methodological issues, but also by *psychological* considerations, such as the suggestiveness, intuitiveness, or vividness of the comparison at the core of the metaphor. For instance, the power of the metaphor which compares the mind to a computer is determined by the fact, among others, that in the common understanding a computer is strongly associated either with enhancing human cognitive activities, or with their artificial reconstruction. This is what makes the analogy so suggestive [Hetmański 2000].

In order to regard the metaphor – which in this approach takes the form of the comparison "object X (modeled) is similar in some respects to object Y (the basis)" – as a starting point for a model, a *theory* concerning object Y (T_Y) is necessary. It is only on the basis of this theory, or specifically, through the concepts which constitute the theory, that it becomes possible to transform the object Y into the model of the object X. In our opinion, there are two parallel ways of carrying out this possibility.

On the one hand, the right segment of the metaphor (containing object **Y**) is **theoretically specified** within the frame of T theory. This means that an approximate description of object **Y**, defining in fact the whole class of objects of some kind, is determined, and thus the range of objects which correspond to this class is narrowed.

On the other hand, the concepts drawn from T theory – the same concepts which were used to characterize object **Y** in detail – are then applied to the object contained in the first segment of the metaphor (that is, **X**). As they are used for an object of a different kind, however, they change their primary meanings. Possibly, their scope changes as well. In this way, a **new** T_X **theory** appears; the assumptions contained in this new theory become the theoretical model of object X.

The clearest situation, from the methodological point of view, takes place in the case of a formal theory, and thus formalized models. In such a situation, T_X theory remains formally identical with T_Y theory. Yet, it acquires new, objective *interpretation*. In other words, the same formal frame T (common to both T_X and T_Y) is used for an object different from the initial one (X instead of Y).[9]

[9] The extent of T theory development can be regarded as a factor determining

If the description above is presented as a series of points, we will obtain the following image of the **modeling procedure** that should always be used by the researcher:

1) The researcher observes significant **similarities** (an analogy) between the modeled object X and the general description of the base object **Y**. In short: $X \sim \mathbf{Y}$ (X is similar to **Y**).[10]
2) The researcher makes the description of object **Y** more **specific** by choosing the Y with a sufficiently rich T_Y theory. In short: $X \sim Y$, $Y \leftarrow T_Y$ (Y has its description in T_Y).
3) The researcher is faced with the task of **constructing the theory** of X, that is, T_X theory which has the same formal frame as T_Y. In short: $T_X = ?$ (T_X is unknown).[11]
4) The researcher constructs the T_X theory by interpreting the terms of T theory; he obtains the description of X basing it on T_X. In short: $X \leftarrow T_X$.
5) The researcher chooses some of the assumptions of T_X which he considers cognitively significant, **obtaining** a (theoretical) **model** of X. In short: $X \leftarrow M_X$, where $M_X \subset T_X$;

Putting these points in a brief and symbolic form we get:

$$(X - \mathbf{Y}, X \sim Y, Y \leftarrow T_Y, TX= ?) \Rightarrow_T (T_X, X \leftarrow T_X, M_X \subset T_X, X \leftarrow M_X),$$

where the notation "$\Rightarrow_T$" means "we move from ... to ..., based on T theory".

The points above generally define the pattern of moving from the informal metaphor ($X \sim Y$) to the initial model of object X, where there is no model M_Y (Y does not have to be an object having a model, it is enough for it to have a certain theoretic description). The metaphor is understood as similarity (analogy) between objects X and Y, as far as some of their features are concerned. Specifying a metaphor understood in this way consists of moving from **Y** to Y and then **reasoning by analogy**, that is,

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the similarity of the model to the metaphor which originated it. A richer theory leads to a more precise model, differing widely from the initial metaphor. A scantier theory leads to a model more closely tied to the metaphor. Consequently, when talking about the computer science metaphor of the mind, we can say that the general thesis "the mind functions similarly to an information processing system" transformed into a model, departs further from the metaphor (moving in the direction of the model) the more advanced are the concepts and the computer science tools used by the creator of the model.

[10] Bold letters are used to differentiate between the base object understood generally (**Y**) and the base object understood specifically (Y).

[11] We must assume that T theory (the formal frame of the model) is a meta-theory (see chapter 2.1).

interpreting T theory anew, in order to achieve T_X by analogy with the way it was interpreted with reference to Y.[12]

The procedure of building the initial model, presented above, is different if the model of the base object Y, $\mathbf{M_Y}$, **exists**. In such a situation, the researcher may omit the first stage of specifying the metaphor (X ~ **Y**), that is, points 1) and 2) – M_Y model determines the exact description of object Y. Furthermore, it constitutes a part of T_Y theory.

The researcher may then proceed directly with the construction of the M_X model, making use of the assumed analogy between the two **mappings**: (a) $X \leftarrow_{TX} M_X$ (M_X maps/describes object X based on T_X theory) and (b) $Y \leftarrow_{TY} M_Y$ (M_Y maps/describes object Y based on T_Y theory). The analogy may be notated symbolically as A: $(X \leftarrow_{TX} M_X) \sim (Y \leftarrow_{TY} M_Y)$; it should be kept in mind that this is a different analogy from the $X \sim Y$ analogy which defines the initial metaphor.

Reasoning on the basis of the analogy A, the researcher carries out points 3), 4) and 5) of the above pattern, that is, he makes use of T theory which is more general and more abstract than T_Y (and more abstract), trying to **interpret** its terms **differently**. The discretion of this interpretation is limited by the MY model which has been chosen by the researcher as a reference point for the new model.[13]

Following the reasoning presented above, we obtain the pattern:

$$\{(X \leftarrow_{TX} M_X) \sim (Y \leftarrow_{TY} M_Y), M_X = ?\} \Rightarrow_T \{M_X, X \leftarrow_{TX} M_X\}.$$[14]

3.2. Computer Science Metaphor and the Models of Mind

In this article, we focus on the computer science metaphor (CSMt) which consists of the comparison of the modeled object with an information processing system. This metaphor provides a natural starting point for partial models of the mind (partial in the sense that they do not refer to the

[12] An important conclusion is to be drawn from these explanations. The statement that Y is a model of X (which is sometimes made – for example, the statement that a digital computer is a model of the mind) is a great mental abbreviation. In fact, the model of X is not Y, but it derives from the theory regarding Y. It derives from it in the sense that the assumptions constituting the model have the same formal configuration as some assumptions concerning object Y.

[13] It has to be noted here that a researcher does not have to (although he may wish to) construct T_X theory. He may confine himself to constructing only the M_X model which is the most cognitively significant element of T_X theory as far as modeling is concerned.

[14] The pattern is portrayed by the example, well-known from the history of science, of the construction procedure of the Bohr atom model (M_X) by analogy to the heliocentric model of the Solar System (M_Y).

mind as a whole, but to certain mental activities and phenomena). With regard to the mental sphere the metaphor will take the form: *"the mind (X) resembles an information processing system (Y)"*.

This formula may be considered a **heuristically justified metaphor** only because it is a good expression of two basic facts about the mind: 1) the essence of mental activities, contrary to physical ones, is the processing of **information** (as opposed to matter or energy) and 2) similarly to information processing systems used to **control** physical systems, the task of the mind is, among others, to direct physical activities of the body on the basis of information which is obtained from the outside the body and suitably processed [Hetmański 2000].

The move from CSMt to a partial model of the mind is performed on the basis of the pattern described in the chapter 3.1. The subsequent steps of its formulation are as follows:

In the first step the researcher accepts the general thesis that "the mind (X) reminds us in some respects of an information processing system (**Y**)." In step 2) he must clarify the vague concept of an information processing system, that is, he has to define the type of system (for example, a rule-based system), as well as describe its structure and the rules of its operation. Proceeding with the necessary specifying procedures, the researcher makes use of the meta-theory, here: computer science. Specifically, he uses a certain chosen theory of data processing (for example, the theory of expert systems).

In the next step the researcher moves from computer science theory (T_Y) to the theory of the mind (T_X). In order to do this, he makes the structure and the functions of the mind similar to the construction and the rules of functioning of the chosen information processing system. For example, if we decided to choose a rule-based system, certain modules of the mind responsible for particular cognitive functions must be specified. Then the functioning of each of these has to be described by rules in the form: "*If A, then B.*" Both the configuration of these rules and the formal schemas of their use or improvement (i.e. algorithms), should remain the same, as they do in the case of the initial information processing system. This is exactly what is required by the postulation of retaining the formal core of T theory, as formulated earlier.

As a result of the aforementioned actions, in specifying the initial metaphor "the mind $\sim$ the information processing system", various computer science models of the mind (CSMM) are constructed which owe their specific form to a choice of a particular base system.

The general concept of CSMM goes as follows: (a) the **formal frame** of the model consists of suitable algorithms and data structures, embedded in the wider context of a particular technique of data processing, (b) all formal computer science concepts are **interpreted** as concepts concerning mental activities, (c) the accepted interpretation aims at **explaining** these activities and/or their artificial **realization**. Again, on the way from the initial metaphor to the final partial model (i.e. the model referring to a certain section of mental activity) a particular technique of data processing must be chosen. The choice of its type determines the type of the model.

It must be noted that the natural background (both theoretical and practical) of CSMM is formed by research on artificial intelligence – research which aims at mechanization, that is, an artificial realization, of some of the human cognitive activities.[15] We should note in passing, that both exemplary models discussed in 2.3 may be considered inspired by research on artificial intelligence, as both artificial neural nets and decision tables belong to this field.

With reference to particular techniques of 'intelligent' data processing one can distinguish – again, as an example, not as an exhaustive list – between the following types of CSMM:

a) **rule-based** models – referring to the theory of symbolic data processing by means of clear rules, such as *'if a premise, then the conclusion'*, implemented in the framework of expert systems [Ignizio 1991];
b) **connectionist** (network-based) models – referring to the theory of subsymbolic data processing in a distributed and parallel way, carried out practically by means of artificial neural nets [Żurada 1992];
c) **evolutionary** (selective) models – referring to the theory of simulated electronic evolution, including, among others, the theory of genetic algorithms[16] [Michalewicz 1992].

[15] One of the typical definitions of artificial intelligence as a discipline is "Research aiming at the realization of activities which require intelligence when they are performed by humans". Consequently, the research aims at the artificial realization of mental activities instead of modeling them. However, constructions created in the context of realization are also used in the context of modeling.

[16] This choice is largely arbitrary – in the authors' opinion, however, it characterizes quite well contemporary research tendencies among computer science experts. What is more, it presents an image of a certain important distinction between the logicistic (referring to logics) and the naturalistic (referring to empirical observations) trends in research on artificial intelligence [Russel, Norvig 1994].

4. Modeling procedure

The characteristics of modeling proposed above are obviously incomplete because they do not take into consideration the dynamics or the **interactivity** of the whole procedure. They account for only one of its stages which consists of the elaboration of the initial model of the phenomenon on the basis of the initial metaphor and the theory specifying its content. The subsequent stages, composing the proper procedure, consist of a gradual modification of the initial model, both for the sake of its formal properties (simplifying the assumptions which constitute the model) and for the sake of confronting the theoretical model with the reality (experimental tests).

4.1. Interactive Modeling Loop

Portrayed in the simplest way, the schema of the proper procedure of modeling a phenomenon X is **linear** and **cyclical** in character (see [Stacewicz 2010]). This means that the schema comprises four stages of modeling which are sequentially ordered and which can be iterated in a loop. These are:

(1) **abstraction** – a procedure in which those *features* of the modeled phenomenon which will be included in the model are specified, while the rest of the features are ignored;

(2) **formalization**[17] – a procedure in which we must refer to the metatheory. That is, we need to choose and make use of formal tools (mathematical theories, computer science theories, algorithms, data structures, etc.) allowing us to describe precisely,usually in a symbolic manner, the modeled phenomenon;

(3) **simplification** – a procedure in which the formal structure of the model is simplified by means of formal transformations in such a way that its initial level of coherence is preserved, together with its initial explanatory and predictive power.

(4) **verification** – a procedure in which features of the model are checked for their adequacy with respect to the described fragment of reality (adequacy), their non-contradiction, or their desired level of non-con-

[17] The abstraction and formalization stages are closely related. Possibly, they constitute a unity. The result of abstraction, that is, the choice of significant features of the modeled phenomenon, depends largely on the formal tool used (a given type of formalism eliminates some types of abstracted features). On the other hand, the initially assumed result of abstraction, that is, the abstracted features, motivate the researcher to choose a given formal tool.

tradiction (coherence), as well as their predictive effectiveness and simplicity (from the point of view of the interpreter).[18] We must add that the model should be checked both separately from other constructions – for example, by drawing certain conclusions from it and then checking their adequacy with respect to reality – and with reference to alternative constructions – for example, by comparing the predictive power or simplicity of various models.[19]

We must emphasize that as a result of the definitional "approximation" of a model, and thanks to the activity of the researcher constructing the model, at stage (4) the procedure of modeling, or arriving at the most adequate model does not end, instead it **enters into a loop**. There is a move to stage (1), in which – depending on the results of verification – features of the modeled phenomenon which are different from the ones highlighted in the previous cycle are accentuated Thus a **different kind of abstraction** is performed, forming the basis for subsequent stages. We must add that, depending on the intensity of the changes introduced within the framework of the new abstraction procedure, the constructor of the model may choose new formal (meta-theoretical) tools, or retain the tools he has used so far.

The four stages of the complex modeling activity, consisting in fact of performing certain cognitive procedures, should be considered with reference to the four elements to which these procedures pertain. These are:

(a) the studied **domain** D – constituting a fragment of empirical reality;
(b) a given **meta-theory** MT – constituting a hierarchically ordered conglomerate of strictly formal theories, micro-theories and schemas (in reference to computer science models, we assume that the highest position in the hierarchy is occupied by mathematical theories, and the lowest by the algorithms and data structures used in them);
(c) the constructed **theory** of the studied domain DT – formally identical with a certain fragment of the meta-theory (in other words, the theory the formal language of which is determined by the meta-theory);
(d) the constructed **model** M – constituting the currently tested fragment of DT theory (the fragment which, in the case of positive verification, validates the DT theory).

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[18] In fact, we could talk here – as Popper did – about falsification tests, the aim of which is verification directed at rejecting the model. See [Popper 2002 (1934)].

[19] We should add here, that schema described above can be considered either in the system [*researcher-model-reality*] for which we assume that the researcher follows the its subsequent steps, or in the system [*model-reality*] for which we look for some automated methods of modeling.

As a result of the four elements mentioned above – D, MT, DT and M – the following characteristics of the four stages of modeling can be given:

(a) **abstraction** concerns the initial choice and the description of these "fragments" of reality – among them the D domain – which the researcher wishes to include in the model. Therefore, it takes place between D and DT (M),

(b) **formalization** means applying a meta-theory MT to give a precise description of the domain D in the form of the model M (in the narrow sense) and the theory DT (in the broad sense). Therefore, it takes place between D, MT and M/DT. This operation can be called an interpretation of a certain fragment of the meta-theory.

(c) **simplification** takes place within the framework of MT (for example, if MT is a deduction theory, particular rules of reasoning apply) and it concerns the model M,

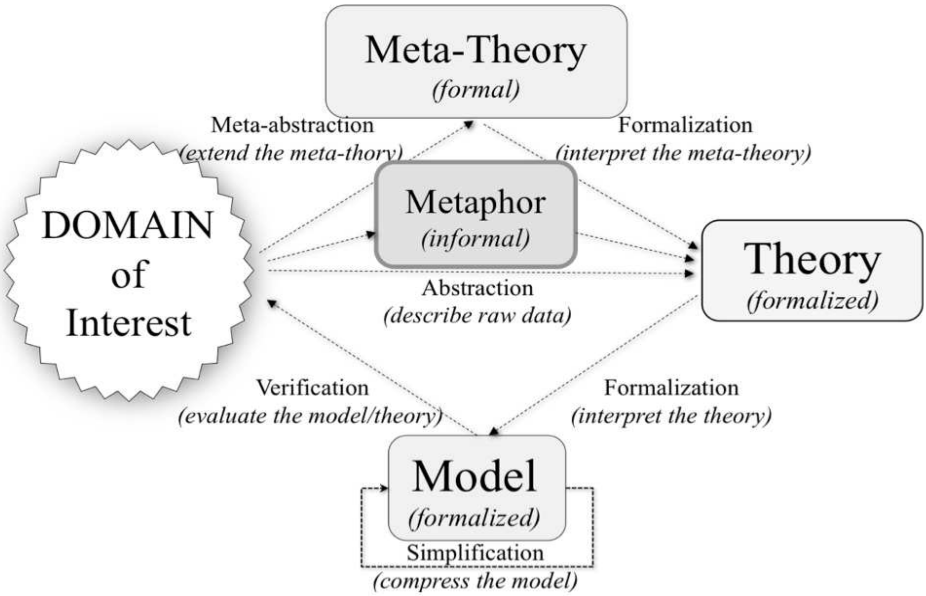
(d) **verification** consists of the confrontation of the model (as well as of the predictions derived on the basis of the model) with a particular fragment of reality, that is, the domain D. Therefore, it takes place between M and D (indirectly, it is the verification of the theory).

We should keep in mind that in certain models – for example, partial models of mind – created using computer applications and/or information processing systems, the initial shape of the model is defined by a **metaphor** (for example, the metaphor of mind as an information processing system).

Consequently, the metaphor has to be **included** in the interactive loop of modeling. It is even possible to note something further: in the modeling practice, as a result of a series of negative verifications of models based on a given metaphor, a need arises for replacing this metaphor with a different one (for example, replacing a metaphor of the mind as a "black box" with a computer science metaphor) Therefore, the presence of the metaphor in the schema of the interactive modeling loop is fully justified.

It should also be noted that the meta-theory used (the choice of which often depends on the content of the current metaphor) is not finite and fully specified. In the course of modeling, mainly as a result of negative verification of subsequent models, a need arises for abstracting from realityor, possibly, constructing *a priori*, new elements of the meta-theory. Such an operation may be called **meta-abstraction**.

These observations are visualized in the chart below.



Considering the terms, explanations and the chart above, it is possible to explain in greater detail what we understand by the **modeling loop**. This loop is interactive, as it engages the researcher at every step. It consists of the three following cycles:

(1) **small simplification cycle** – this loop, consisting of a purely formal/syntactic elimination of the superfluous/excessive elements present in the model under construction, may be created automatically, that is, without the participation of the researcher. Machine learning algorithms (for example, decision tables reduction algorithms) prove very useful for the purpose of its computer-aided implementation.

(2) **proper modeling cycle** – this loop consists of cyclically iterated procedures of abstraction, formalization, simplification and verification using a meta-theory, and sometimes including initial reference to a metaphor. The whole process remains under the researcher's control (deciding, for example, on the course of abstraction and formalization). It is possible, however, to think about its mechanization (also using learning algorithms), in which case the role of the researcher would be rather limited; that is, it would consist of assessing temporary models.

(3) **wide modeling cycle** – in which it is acceptable to construct new elements of meta-theory and to make use of new metaphors (new with respect to the one which initiated the whole procedure).

4.2. Modeling Procedure in the Context of Computer Science

Examining the aforementioned procedure in the context of computer science, we must remind the reader (in accordance with paragraph 2.2) that in this context modeling is understood as **programming** – embedded in mathematics and referring to various computer science techniques – aiming at designing a modeling application and/or a system controlled by this application.

Assuming this perspective, we should, however, inquire in general about the functions of computer science,including programming, in the process of modeling. The answer is connected with an important distinction between a) computer science as a **supporting tool** in modeling, and b) computer science as a domain to which the application-model (computer science model) is supposed to belong.

Therefore, it is necessary to differentiate between: a1) the procedure of construction of any model with the active use of various computer science tools by the researcher (including, among others, algorithms of knowledge acquisition and reduction) and b1) the procedure of constructing a computer science model, that is, a (theoretical) model in the form of an application based on an algorithm (in a broader sense: based on a mini-theory of data processing). The distinction suggested here is not an alternative: the situation b/b1 may be treated as a special case of the situation a/a1.

From now on, we will focus on the b/b1 situation, bearing in mind, however, that contemporary computer science, as the most efficient tool of the automation of cognitive processes, is used in almost every modeling procedure.

Having limited our analysis to the situation b/b1, we can generally characterize subsequent **stages** of modeling, each time paying attention to the possibility of the **automation** of a given stage. This is an extremely interesting issue, since the automation of various processes is the most important and, in many cases, the already achieved aim of computer science research.

We will start from the two interwoven stages of **abstraction** and **formalization**. They concern a description of the modeled phenomenon in the precise terms of data structures (or, in broader sense: methods of knowledge representation), considered usually within the framework of a certain general technique of data processing. For example, the representation of knowledge in the form of formulas for classic or First Order Logic (FOL) is inseparably interwoven with rule-based techniques of data-processing, while representation in the form of neural nets is intertwined with connectionist techniques, and representation by means of genetic structures with evolutionist techniques.

When the researcher has made the meta-theoretical choices, that is, when he has decided on a particular formal shape of the model, he can proceed with the **interpretation** of formalisms in the domain in which he is interested. He does not need to build a whole theory of this domain, he may proceed directly with the construction of some of its fragments, that is, a particular application-model which will be used in the chosen domain. Here we have to make two remarks about automation: (1) automation of the abstraction stage would be possible on condition that there existed a universal schema of the choice of more and more promising features of the modeled phenomenon (as far as the adequacy of the model is concerned); (2) as far as modeling can be considered a domain of the human mind, the automation of the formalization process should be feasible on condition that there existed a universal formalism (for example, a logical calculus) or, at least, a finite class of formalisms which could describe mental activities.

At the subsequent stage, that is, the **simplification** stage, the researcher must make use of a certain computer science tool to simplify the initial application-model. It seems that methods of *machine learning* – concerning reduction of knowledge – may become most widely used here [Mitchell 1997]. One such method is the reduction of decision tables, mentioned in paragraph 2.3. Among other methods, those based on self-organizing neural nets and genetic algorithms can be mentioned. Automation is absolutely possible here, due to the algorithmic character of these methods.

At the next stage the researcher has to proceed with the **verification** of the application-model. That is, he has to check whether the simplified application works, whether it realizes the modeled process (in the sense of obtaining the same results), whether it displays significant functional-structural similarities to the known features of the modeled phenomenon, whether simpler and more efficient applications exist, reflecting the modeled phenomenon...

Having done a suitable number of precise and meticulous tests, the researcher may consider the application a sufficiently good temporary model, or may reject the model in order to refer to another form of the computer science metaphor and/or other formal tools of computer science.

As an example illustrating the above remarks, we will consider an issue which is particularly important as far as the contemporary use of computer science is concerned: the process of using **concepts** in order to recognize objects of a particular type. The object of modeling will be a concept,[20]

[20] In the general sense, concept may be understood as a decision function which maps

considered with respect to the possibility of recognizing objects based on their chosen features (for example, recognizing *fruit* based on its *color*, *shape* or *taste*). Keeping this example in mind, let us have a closer look at each of the stages of modeling.

At the first stage – the abstraction stage – the constructor of a model has to choose the **significant features** of objects to be recognized and narrow down the further steps to these features. Let us assume that he chooses only four such features (*color*, *shape*, *taste*, *time of ripening*) and that there is a particular class of values connected with each of them (for example, for the feature of color he chooses the following values: *red*, *green*, *yellow*, *orange*, *violet*).

At the second stage, that is, at the stage of formalization, a **type of concept representation** should be determined – a representation schema embedded in a relatively rich formal theory which will enable operations on similar representations. Let us assume that the constructor of the model chooses Z. Pawlak's theory of a rough set [Pawlak 1991] and the method of representing concepts as decision rules which derives from it (see the example from paragraph 2.3). In this case the concept corresponds to an alternative of decision logic implications in the antecedents of which there are conjunctions of values of the features which have been chosen, and in the consequents of which there are numbers 0 and 1 (0 – indicates that a given rule is a negative description of a concept, 1 – indicates that a rule is a positive description).

At the next stage, that is, at the stage of simplification, a method has to be chosen (at best, an automated method) which will allow for the maximum **simplification (compression) of the model**. In this case it involves the number of rules and their elements, all of which combine to create a representation of the concept. Let us assume that an algorithm of reduction is chosen, derived from the theory of a rough set mentioned in paragraph 2.3.[21] Having performed the simplification as understood in this way, the model constructor has to assess the simplified model, for example, as far as the degree of the performed reduction is concerned, and thus he

a set of objects into a set of binary decisions (1 – yes, the object is a designatum of the concept; 0 – no, the object is not a designatum of the concept). In psychology, concepts are usually treated as cognitive representations of the above mentioned decision function.

[21] This algorithm leads to a minimalized class of rules which provides the same ability to recognize the designata of a concept as does the initial class. In other words, if a class of decision rules is understood as a model of a concept, this algorithm leads to a simplified model.

proceeds to the verification stage.[22] If the degree of reduction is not sufficient in his opinion, he can return to the stage of abstraction and choose another class of features and their values. In this way, the modeling cycle may start all over again.

5. Final remarks

The reconstruction of modeling procedure proposed here, in the computer science environment, should be considered as one of the **possible models** of what is in fact carried out by theoreticians and practitioners when constructing computer science models of phenomena. Our model has an approximate character (as any model has) and it reflects general frames of the process which, in reality, is much more complex and can certainly be expressed (i.e. modeled) in many different ways. What we have presented, however, justifies the formulation of a certain vision of computer science as an ever more efficient modeling tool.

It seems that scientific research in this field, particularly in the branch of so-called **artificial intelligence**, heralds a great breakthrough in modeling practice. Within the next decade, the incredible possibilities of the accumulation of knowledge in databases, as well as new computer functions imitating the abilities of human intellect, will enable even closer cooperation between researchers representing various branches of knowledge. This will prove efficient inasmuch as man in his interaction with the computer will be able to think *together with machines*. It must be emphasized that machines will not think instead of humans, but humans will *think* using machines as their intellectual "partners" (see [Włodarczyk 2009]).

In other words, information processing machines will become a more efficient tool of human thinking than they have been so far. Even today's achievements in computer science make one incline towards this conviction. For nowadays computers can to some extent imitate the most crucial activities of the human mind, namely *reasoning* (for example, deduction) *learning* and *inventiveness* (enabling development). In some respects, the abilities of these machines exceed even the abilities of the human mind.

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[22] It should be noted that the procedure of simplification based on the proposed algorithm of reduction does not change the most crucial property of the model which is the ability to recognize the designata of a concept. Therefore, when verifying a model, its constructor cannot consider this ability, but, at most, the simplicity of the model.

In the context of contemporary computer science, thinking with machines may be provided with the technical label of *data mining*. This is the (undoubtedly provisional) name of a new, dynamically developing branch of computer science which includes various computational methods such as knowledge discovery in databases, fuzzy logic and decision logic, formal concept analyses, logic of distributed systems, granular computing (also called methods of computing with words), and automated discovery.

We trust that, in the very near future, this discipline will provide a series of new, formal tools which will allow for a significant increase in the effectiveness of the interactive modeling trial-and-error loop described in this article.

SUMMARY

The article deals with computer science models (CSMd), that is, formal constructions which are described theoretically in the language of computer science (the language of algorithms and data structures), and which can therefore, be implemented in the form of applications and activated on a computer.

After distinguishing different kinds of CSMd (e.g. theoretical and real) and presenting some examples of CSMd (especially in the field of mental phenomena) we discuss in detail the modeling procedure. This procedure can be initiated by a metaphor (understood as an initial, informal image of a studied phenomenon), has a cyclical and open character, and – according to our methodological reconstruction – consists of four stages: abstraction, formalization, simplification and verification. We discuss these stages in the context of computer science, referring to four elements: the studied domain, a meta-theory (always formal), the constructed theory of the studied domain (formalized in the language of meta-theory), and the constructed model (always temporary). We present a simplified scheme of the whole procedure and identify three cycles of the modeling loop: small, proper and wide.

Finally we claim that contemporary CSMd (especially computer science models of the mind) should be constructed using artificial intelligence tools, such as machine learning and data mining techniques.

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