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Understanding Systems: A Taxonomy and Performance Factors

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ABSTRACT

Some basic concepts and definitions of understanding are reviewed with references to their philosophical roots. A taxonomy of 40 types of understanding is offered based on the product of understanding and the characteristics of the understanding process, meta-model used, and understanding systems. The elements as well as the factors affecting performance of understanding systems are explained.

INTRODUCTION

Background

In the study of natural phenomena, the role of simulation is often cited as "to gain insight" which is another way of expressing "to understand." Conceived from this perspective, Nalimov even defines a model as "a question put by the researcher to nature." (Nalimov 1981). This study dissects the concept of "understanding" for two purposes: to provide (1) a taxonomy of understanding and (2) to provide a categorization of the elements and performance factors of understanding systems. At this level of abstraction, the concepts covered in this article are applicable to objects or systems that can be studied by simulation, to simulation software as well as to software in general and to any other object or system.

Understanding is one of the important philosophical topics. From a pragmatic point of view, it has a broad application potential in many computerized studies including program understanding (WPC'93, IWPC'99), machine vision, fault detection based on machine vision as well as situation assessment. Therefore, systematic studies of the elements, structures, architectures, and scope of applications of computerized understanding systems as well as the characteristics of the results (or products) of understanding processes are warranted. Ability to understand is related with intelligence both in natural and in engineered systems.

The scope of applicability of understanding is very broad. Accordingly, it may require appropriate knowledge processing abilities as well as different types of background knowledge. The intelligibility and unintelligibility of an entity may not be necessarily absolute characteristics. It may simply reflect the ability or the inability of the system, which attempts to understand it. An entity can be at the same time intelligible and unintelligible for different understanding systems.

Definitions

Dictionary definitions of "to understand" include the following:
- to seize the meaning of,
- to accept as a fact, believe,
- to be thoroughly acquainted with,
- to form a reasoned judgment concerning something,
- to have the power of seizing meanings, forming reasoned judgments,
- to appreciate and sympathize with, to tolerate,
- to possess a passive knowledge of a language (Webster 1987).

Dewey (1910/1991) relates understanding with meaning by stating that if A cannot understand B, B does not have a meaning for A. However, there are still challenges yet to be achieved for systems to understand semantics and pragmatics in addition to understanding elements and morphologies.
Zeigler (1986) provides the following clarification for knowing:

> "We say that a system 'knows about' a class of objects, or relations, if it has an internal relation for the class which enables it to operate on objects in this class and to communicate with others about such operations. Thus, if a system knows about X, a class of objects or relations on objects, it is able to use an (internal) representation of the class in at least the fol-

lowing ways: receive information about the class, generate elements in the class, recognize members of the class and discriminate them from other class members, answer questions about the class, and take into account information about changes in the class members" (Zeigler 1986).

From this point of view, knowing and computerized understanding can be taken as synonyms. However, one should remark here that knowing (something, somebody, some event, etc.) refers to the result of the process of acquiring knowledge and not the knowledge processing activity required to know.

> "Biermann (1990, pp. 377-394) gives an example of how a system could understand that an object is a chair. Such a system would have a knowledge base about a chair where the knowledge is expressed in terms of a semantic network. Based on the explanation of the system's characteristics, he gives the following definition of understanding:
>
> The understanding of a perception '... with respect to a body of knowledge involves finding a set of self-consistent links between the parts of the knowledge structure and the parts of the perceived data. After such a linkage is made, the intelligent being can follow arcs in its knowledge base to obtain innumerable useful facts, the name of the perceived objects, the names of its many parts, their relationships to each other, the uses of the object, and all other information available in its knowledge base. ...'
>
> Reasoning is the process of finding or building a linkage from one entity in memory to another. There must be an initial entity, a target entity, and a way of choosing paths from the initial entity toward the target." (Ören 1992, pp. 5-6).

In this article, the interest is systems to be engineered to have understanding abilities. The term understanding is used as a shortened form of computerized understanding (or computer understanding). The concepts are also applicable to computer-aided and computer-assisted understandings). From a computerized knowledge processing point of view, the following definition of understanding is proposed:

Understanding an entity (a thing, a concept, an event, a system, or the like) is a mapping between the perceived and analyzed knowledge about the entity and a meta-model (i.e., a more general knowledge) of the entity. The term understanding refers both to the process as well as to the product. The questions "how to understand?" and "what to do with the understood knowledge?" should be considered separately. An important aspect which relates them is that the second question has to be taken into consideration while determining the aspects of an entity to be understood and the level of details (i.e., granularity) of understanding.

TYPES OF UNDERSTANDING

A taxonomy of understanding is given in Table 1 where several types of understanding are characterized with respect to the product of the understanding process, the understanding process, the meta-model used, and the characteristics of the understanding systems.

Types of Understanding Based on the *Product* of the Understanding Process

Product of the understanding process can be discriminated according to its domain, nature, scope, granularity (i.e., level of detail), and reliability.

Whitehead (1938/1968, pp. 45-46) identifies internal and external understandings, which are both, related with the domain of the product of the understanding process.

- *Internal understanding* involves the elements of a system and their relationships as well as the attributes of the elements and the relationships. The elements, relationships, and attributes can be time-invariant or time-varying. In internal understanding, a system is treated as a white box.
- *External understanding* involves relationships of a system and its environment. The relationships can be time-invariant or time-varying. In external understanding, a system is treated as a black box.

According to the nature of the product of the understanding process, one can discriminate lexical, syntactic, morphological, semantic, and pragmatic understandings.

- *Lexical understanding* is the lowest level of understanding and discriminates the elements of an entity.
- *Syntactic understanding* discriminates how the elements of an entity are related.
- *Morphological understanding* discriminates how relevant forms and structures are represented.

- *Semantic understanding* involves with meanings attached to the elements of an entity as well as to their relationships.
- *Pragmatic understanding* involves with the interpretations of the intentions, which might be attributed to the elements of an entity as well as to their relationships.

According to the scope of understanding, focused, broad, and multiaspect understandings can be identified.

- *Focused understanding* involves knowledge about one or a few characteristics of an entity.

Table 1. A Taxonomy of Understanding

Criteria related with the characteristics of the		**types of understanding**
product of the understanding process	domain	- internal understanding - external understanding
	nature	- lexical understanding - syntactic understanding - morphological understanding (understanding the structure) - semantic understanding (understanding the meaning) - pragmatic understanding (understanding the intention)
	scope	- focused understanding - broad understanding (understanding several or all characteristics) - multiaspect understanding
	granularity (level of detail)	- coarse understanding - in-depth understanding (detailed understanding)
	reliability	- reliable understanding - valid understanding, - verified understanding - unreliable understanding - invalid understanding, - unverified understanding
understanding **process**	direction	- top-down understanding - bottom up understanding
	directness	- apprehension (direct understanding) - comprehension (indirect understanding, mediated understanding) - logical understanding)
	accumulation of knowledge	- re-initialized understanding (tabula rasa understanding) - cumulative understanding
meta-model used	fixed	- single vision understanding - dogmatic understanding
	evolvable	- learning understanding
	replaceable	- multivision understanding (switchable understanding)
understanding **system**	*initiative* of the understanding system	- autonomous understanding - delegated understanding - remote understanding
	number of understanding system	- individual understanding - group understanding - distributed understanding
	knowledge sharing features of understanding system	- repetitive understanding - cooperative understanding
	mechanisms to *disseminate* the result of understanding process	- understanding per command - understanding for subscribers - broadcasted understanding - blackboard understanding - legacy understanding

- *Broad understanding* is understanding several or all characteristics of an entity.
- *Multiaspect understanding* is understanding of multiaspect systems (Ören 2000). In multiaspect, understanding several meta-models can be used to understand several aspects of an entity. These aspects may even be contradictory. Multiaspect understanding is different from broad understanding.

In music for example, one can be as broad as understanding music, or understanding Western music, or one can focus to understand Baroque music, Vivaldi, or a musical notation system, a suite of notes, or a single note. Furthermore, these understandings can be based on textual, graphic or audio materials.

According to the level of detail (or granularity) of the product of the understanding process, we distinguish coarse and in-depth understandings.
- *Coarse understanding* does not involve detailed knowledge about an entity.
- *In-depth understanding* involves understanding of the details of the characteristics of an entity.

According to reliability and dependability, one identifies valid understanding, invalid understanding, verified understanding, and unverified understanding.

To have *valid understanding*, appropriate quality assurance techniques should be used to ensure reliability and dependability of the meta-model and the other elements of an understanding. Otherwise, one has *invalid understanding*. Similarly, the term "*unverified understanding*" refers to the understanding obtained by a system where there may be flaws in the computerization of its elements. Otherwise, one has *verified understanding*.

Types of Understanding Based on the *Understanding Process*

Several types of understanding can be identified according to the direction and the directness of the understanding process as well as the accumulation of the understood knowledge.

As Whitehead (1938/1968, pp. 58) clarifies it, understanding has two modes of advance: the gathering of detail within assigned pattern, and the discovery of novel pattern with its emphasis on novel detail. We label these two types of understanding as top-down and bottom up understandings.

- *Top-down understanding* starts with background knowledge (meta-model) about an entity to gather knowledge about it.
- *Bottom up understanding* starts with an analysis or perception of an entity and maps relevant knowledge to a meta-model of it.

Directness of the understanding process discriminates two basic types of understanding: apprehension and comprehension.

- *Apprehension* is direct understanding (Dewey 1910/1991, p. 120) or self-evidence (Whitehead 1938/1968, p. 58).
- *Comprehension* is indirect or mediated understanding (Dewey 1910/1991, p. 120).
- *Logical understanding* is indirect understanding where logical inference is used as a means for the attainment of an understanding. As Whitehead (1938/1968, p. 50) states it, proofs are the tools for the extension of imperfect self evidence.

According to the accumulation of knowledge, re-initialized and cumulative understandings can be distinguished.

- Re-initialized understanding does not depend on the previous understanding process(es). At the beginning of an understanding process, any remnant understanding from previous understanding process(es) is ignored. Accordingly, re-initialized understanding can also be called tabula rasa understanding.
- *Cumulative understanding* builds up an understanding on top of previous understanding(s).

Types of Understanding Based on the Characteristics of the *Meta-model*

The meta-model can be fixed, evolvable, or replaceable. Accordingly, one can distinguish single vision understanding, learning understanding, and multivision understanding.

- *Single vision understanding* is based on a single meta-model. If the meta-model is not fully questioned and justified, single vision understanding is *dogmatic understanding*.
- In *learning understanding*, the meta-model used in understanding may be changing (evolving) through time. Hence, the term learning understanding. In learning understanding, several types of learning approaches may be applicable.
- *Multivision understanding (switchable understanding)* refers to general purpose understanding systems that can switch to an appropriate meta-model to understand characteristics of different sets of entities.

Types of Understanding Based on the Characteristics of the *Understanding Systems*

Characteristics of understanding systems such as initiative, number, knowledge sharing features as well as mechanisms to disseminate the results of understanding process can be used to further discriminate understanding.

Most importantly, reliability and dependability of understanding systems should be properly addressed to assure reliability and dependability of the understanding to be obtained by such systems.

To clarify the role of the initiative taken by an understanding system, three types relevant systems, or modules can be identified. They are: an understanding system (A), an initiator of the understanding process (B) and a user of the knowledge generated by the understanding system (C).

Understanding system performs the necessary operations of the understanding process and generates k, the understood knowledge.

Initiator of the understanding process activates the understanding system. As a special case, an understanding system can activate itself.
User of understood knowledge may not need the activation of an understanding system if the perception in question is already understood and exists in a database. In this case, a database holding previously understood knowledge and associated perceptions has to be consulted by an appropriate module.

According to the initiative taken by an understanding system, two types of understanding can be distinguished: autonomous and delegated understanding.

- *Autonomous understanding* involves with a system, which initiates and performs the understanding process. Such a system may or may not use the product of the understanding process.
- *Delegated understanding* involves at least two systems (or modules): one, which initiates directly or indirectly the understanding process. The initiator or another system can use the product of understanding.
- *Remote understanding* is a delegated understanding where software modules or meta-models used in understanding exist at remote locations. Intranets, internets and the Internet* are natural media for the realization of remote understanding.

In an understanding system, there may be only one or several understanding elements. Accordingly, one can distinguish individual and distributed understandings.

- *Individual understanding* involves one single understanding system.
- *Group understanding* involves with understanding subsystems. They may have same or distinct understanding abilities. In the latter case, they can be specialized in understanding different entities or different aspects of some entities. A special type of group understanding is distributed understanding.
- *Distributed understanding* involves with two or more understanding units located on different computers.

Based on the knowledge sharing features of a group understanding system, there are two types of understanding: repetitive understanding and cooperative understanding.

- *Repetitive understanding* involves several understanding systems where each of which performs similar understanding processes.
- *Cooperative understanding* occurs in group understanding systems (with possible partial repetitive understanding). Some of the understanding subsystems are specialized understanding systems; therefore, functionally they can complement each others abilities.

According to the mechanisms to share the results of understanding, the following can be discriminated: understanding per command, understanding for subscribers, broadcasted understanding, blackboard understanding, and legacy understanding.

- *Understanding per command* is the understanding performed upon activation of an understanding system.
- *Understanding for subscribers* is performed automatically for units that already indicated their preferences.
- *Broadcasted understanding* makes available the understood knowledge to all units by delivering the knowledge to them.
- *Blackboard understanding* posts the understood knowledge on a common area; the units can fetch the relevant knowledge, if they have access permission. *Blackboard understanding* can also be used in group understanding where knowledge understood by different understanding subsystem is made available to any subsystem of the understanding system or to any other system which can access the blackboard.
- *Legacy understanding* bypasses the understanding process and relies on understanding stored in a database.

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* A *network* consists of two or more computers connected together so that they can share resources.
Two or more national and/or international networks connected together form an *internet*.
An *intranet* is a private network inside an organization or a company. An intranet may be a simple network or an internet.

The *Internet* is the international collection of interconnected networks that all use the TCP/IP (Transmission Control Protocol/Internet Protocol).

UNDERSTANDING AND SOFTWARE AGENTS

A software agent is a software module with cognitive abilities such as perception, reasoning, motivation, goal processing, and goal-directed knowledge processing. The concepts associated with understanding systems are very well suited for agent-based software architectures. Therefore, it is expected that most, if not all understanding systems will be implemented as agent-based software including mobile agents. Any understanding term can be used with the term agent to denote an agent or a multiagent system having the relevant understanding characteristics. Furthermore, several synergies, such as agent-based learning understanding seem plausible. Some types of understanding agents are listed in Table 2:

Table 2. Some Understanding Agents

blackboard	understanding agent
broad	understanding agent
cooperative	understanding agent
delegated	understanding agent
distributed	understanding agent
external	understanding agent
focused	understanding agent
in-depth	understanding agent
individual	understanding agent
internal	understanding agent
lexical	understanding agent
remote	understanding agent
repetitive	understanding agent
semantic	understanding agent

ELEMENTS OF UNDERSTANDING SYSTEMS

A system **A** can understand an entity **B** iff three conditions are satisfied:

1. **A** can access **C**, a meta-model of Bs.
   (C is the knowledge of A about Bs.)
2. **A** can perceive and analyze **B** to generate **D**.
   (D is a perception of B by A.)
3. **A** can map relationships between **C** and **D**.

Therefore, an understanding system needs to have the following three basic elements: a meta-model of the entities to be understood, a perception element and an analyzer and a comparator to map a perception of an entity to be understood with the meta-model (Figure 1).

FACTORS AFFECTING PERFORMANCE OF UNDERSTANDING SYSTEMS

A system's ability to understand an entity **B** depends on the restrictions on the three conditions; i.e., (1) on the existence of a meta-model and accessing it, (2) on the perception and analysis of the entity and (3) on the mapping abilities of its comparator. Therefore, the characteristics of these conditions can also be interpreted as factors affecting the performance of understanding systems.

Characteristics of and Accessing to the Meta-Model

- A system that does not have basic knowledge (i.e., a meta-model) about an entity cannot understand it.
- A system that does not have basic knowledge (i.e., a meta-model) about a characteristic of an entity cannot understand it.
- The scope of understanding is bounded by the types of knowledge in the meta-model.
- The level of details (i.e., *granularity*) of the meta-model determines the discrimination ability of the understanding system.
- The content and granularity of the meta-model depend on the types of knowledge required from the understanding system (i.e., the types of questions it should be able to answer.)
- It is possible to change the aspect, scope, or granularity of understanding, by changing the meta-model. Therefore, understanding systems may exist with single or several meta-models. Depending on the sophistication of the understanding system, the most appropriate meta-model can be selected autonomously. Meta-models can also exist on networks. Depending on the nature of an understanding process, a meta-model can be searched and located on the Internet, on internets and/or on intranets.
- Access time to the meta-model affects the speed of understanding.

Perception / Analysis Abilities

There are two different cases (i.e., perception and analysis) depending whether or not an entity to be understood is submitted to the understanding system. In the case of analysis, B, the entity to be understood is submitted as an input to the understanding system A. Therefore, A needs to analyze B with respect to the meta-model C. In the case of perception, the understanding system A may have or may be given the goal to perceive and then understand an entity B. In this case, A needs to keep track of some external or internal events; and then recognize, classify, and filter them to form D, a perception of B.

- Perception necessitates conception; therefore, a system cannot perceive an entity if it does not have a meta-model (or knowledge) about it.
- What cannot be perceived or discriminated in the analysis cannot be understood.

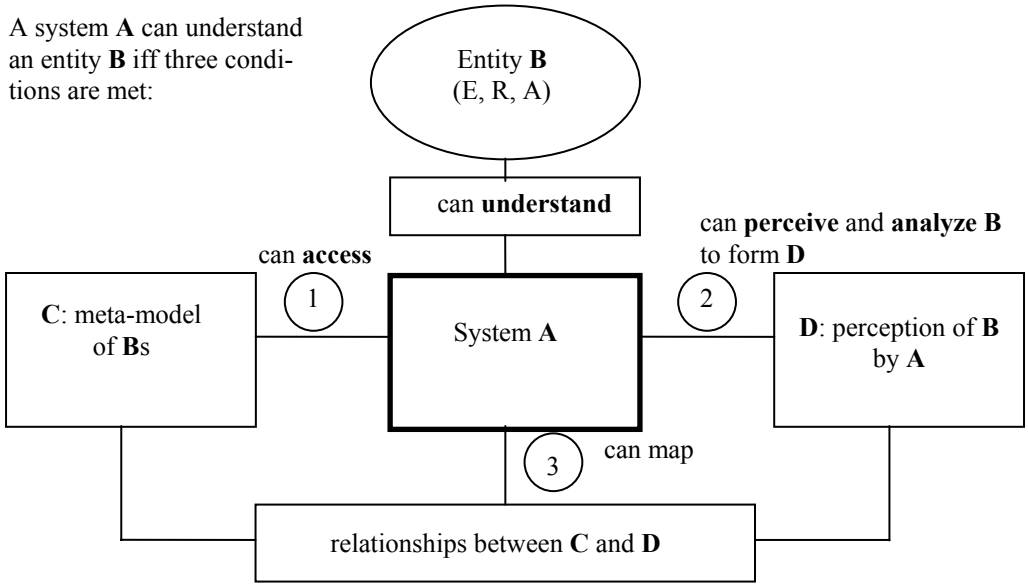

Figure 1. Elements of an Understanding System

- The levels of details (granularities) of the perception and analysis determine the granularity of understanding.
- A meta-model-based implementation of the perception element and the analyzer would allow the realization of flexible software architecture. In such a case, one can modify the abilities of an understanding system by changing or updating the meta-model.
- The speeds of perception and analysis affects the speed of understanding.

Mapping Ability

- To understand an entity **B**, a system **A** needs to perform a mapping between a meta-model **C** of **B**s and **D**, a perception of **B** or the result of analysis of **B**.
- The characteristics of the relations, (e.g., detectable, found, or non-existent relations) affect the limit of understanding.
- Implementation remarks similar to the perception and analysis abilities do also apply for mapping abilities.
- The speed of mapping affects the speed of understanding.

CONCLUSION

Understanding is an important ability for advanced computerization. Some application areas are program understanding, vision, vision for quality assurance, and situation assessment. In this article, after a review of some basic concepts and definitions of understanding a taxonomy of 40 types of understanding is offered. In addition, the elements as well as the factors affecting performance of understanding systems are explained. It appears that agent-based software is an appropriate way to implement understanding systems. Switchable understanding also appears to be a promising paradigm to implement flexible and powerful understanding systems.

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BIOGRAPHY

Dr. Ören has been active in simulation since 1965. His interest areas include: (1) advancement of the methodology of simulation (including synergy of artificial intelligence techniques such as software agents and understanding, simulation, and system theories); (2) software systems engineering, including high-quality user/system interfaces, computer-aided problem solving environments, and program generators from high-level specifications; and (3) reliability issues of modelling and simulation, software, and AI applications.

His recent interest areas include ethics in simulation that he considers as the missing link in VV&A studies as well as the use of simulation in education and training for conflict management and for peace support.

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