Characteristics of Computational Intelligence
(Quantitative Approach)

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Abstract

These days, intelligence is one of the features of software agents. However, developing this feature via a systematic software engineering approach suffers from some shortages. One of the open issues is related to specifying intelligence features that are expected from intelligent agents. The source of the problem is different definitions of intelligence that are presented from different perspectives. Consequently, there is not a predefined set of characteristics for intelligence that can be used as a baseline for specifying intelligence requirements of the system. As a result, intelligence is defined (or interpreted) differently between various stakeholders of the system. This will lead to the ambiguity of the requirements, which is the source of serious problems in developing software systems.

In this paper, we look at intelligence of agents from a software engineering point of view. In this way, we analyze more than 70 different definitions of intelligence (in different areas such as public notions, psychology and AI) to extract different characteristics that are considered as features of intelligence. By eliminating non-computational capabilities of intelligence, we investigate a set of characteristics of computational intelligence.

In this way, we use a quantitative approach. We rank identified characteristics according to the frequency of their appearance in various definitions. The result is that learning, adaptation to new situations and environment, goal-orientation, problem solving, acquiring and using knowledge and reasoning are the top ranked issues of intelligence. Because the extracted features belong to different levels of abstraction, we classify them into four groups that are non-functional, general capabilities, basic AI techniques and Infrastructural. In addition, we investigate the relationship between intelligence characteristics (e.g. learning) and the other quality attributes of software systems.

Introduction

Usually, intelligence is an expected capability of software agents. One of the promises of agent oriented software engineering is to bring artificial intelligence findings to everyday practices of software development [1]. We believe that as intelligence is one of the features of software agents, similar to the other features of software systems, it should be developed via applying a complete process, which covers all the activities of software development such as requirement engineering, analysis, design, implementation and test.

However, some research have been performed on analysis and design of intelligence features of the agents (such as autonomy [2], reasoning [3] and learning [4]), but currently this process is more focused on implementation of artificial intelligence software systems. Consequently, by ignoring requirements specification, analysis and (somehow) design of intelligence features, implementation suffers from a complete and comprehensive input from earlier phases of software development. Taking into account the cost and probability of the failure in such an incomplete process, importance of developing intelligence via an engineering approach is made obvious.

In a complete software engineering process, the first activity is defining and specifying requirements and expected features of software system. By considering intelligence as a software requirement, a set of characteristics is needed to be used as a reference for defining intelligence requirements. But, unfortunately, intelligence itself is a vague term and there are different definitions for it [6]. Consequently, there is not an agreement on intelligence, not only between customers and developers but also between experts of each group. This will result ambiguity in intelligence as a requirement, because it is interpreted differently by different stakeholders of the system.

To solve this problem, in this paper we present a software engineering view on intelligence as a requirement of

software agents. Our approach is decomposing intelligence - as an ambitious term- to a set of more concrete features or characteristics that are considered as elements of intelligence. In this way, we perform a quantitative analysis on various perspectives of intelligence in different fields (psychology and AI). According to this approach, we can distinguish the main features of intelligence based on the experts' point of view. The frequency of each feature in different definitions can be interpreted as an evidence of implicit agreement on it as a feature of intelligence. To achieve this goal, we take into account more than 70 different definitions of intelligence which have been presented by experts in psychology and AI, in addition to the popular notions about intelligence (which are presented in dictionaries and encyclopedias) and we extract different issues that are mentioned in them as characteristics of intelligence.

Our survey shows that there are 28 distinct characteristics in these definitions. By omitting non-computational characteristics and features that are trivial capabilities for machines, we consider 16 characteristic as computational intelligence features which are ranked based on their frequency and importance in various fields.

The main contribution of this work is that it breaks down intelligence into a set of more concrete characteristics that can be defined and specified as requirements of software agents. The result of this research is a set of characteristics (or features) which can be considered as computational intelligence requirements. This set can be used as a basis for eliciting and specifying intelligence requirements of the system. To this end, requirements engineer uses this set of features as a common language between different stakeholders of the system to interpret intelligence from their point of view. This activity is the first step for moving towards a complete software engineering process for intelligence requirements of agents. Consequently, it can be used as a basis for analysis, design, implementation and test of these features.

The remainder of this paper is organized as follows: In Section 2, we analyze different definitions of intelligence in public notion, psychology and AI. In Section 3, we present the set of characteristics for computational intelligence by analyzing the results of Section 2 and we also classify these characteristics into four main groups. In Section 4, we investigate the relationship between learning (as an intelligence characteristic) and non-functional requirements of software systems. Finally, in Section 5, we conclude and introduce further works of this research.

Analyzing Different Definitions of Intelligence

During last century, various researches have been performed on human and artificial intelligence. Despite such a long history, still there is not a standard definition of intelligence neither in psychology for human intelligence nor in AI for artificial intelligence.

One of the methods that can help us to overcome ambiguity of a term is to describe it via its characteristics. For example, in software engineering quality –as a vague term, is defined via its characteristics such as reliability, usability, etc. [5]. Therefore, to solve the same problem for intelligence, it can be defined via its characteristics as well. In this way, we break down different definitions of intelligence to investigate attributes that are identified as characteristics of intelligence.

Our observation leads us to believe that intelligence is not a single unitary ability, but rather a composition of several functions. This result confirms our first hypothesis for defining intelligence via its characteristics that helps us to specify intelligence via its features in software systems. This interprets intelligence (as a vague requirement) to a set of definable features of the system.

In the following, we analyze definitions of intelligence in three categories. Our analysis is performed on a set of definitions that is considered as the largest and most well-references collection on intelligence [6]. It contains 71 definitions of intelligence in psychology, AI and popular notions about intelligence.

The goal of this analysis is to distinguish characteristics that are considered as elements of intelligence according to the experts' point of view in each field.

Public Notions of Intelligence

There are 18 definitions in this group. This group represents definitions that have been proposed by groups or organizations and definitions of intelligence given in dictionaries and encyclopedias [6]. We consider these definitions as popular notions about intelligence because they construct or represent general ideas about intelligence in public. Since customers are a main group of stakeholders for defining requirements of the system, this category of definitions is important in our survey because it represents customers' point of view about intelligence.

By reviewing these definitions, we identify the following characteristics as attributes of intelligence: learning and understanding (e.g., facts, truth, meanings) (12 times each), reasoning (9 times), ability to adapt to the environment or new situations (6 times), capability to solve problems (5 times), capability to acquire and apply knowledge (5 times), profit from experience (4 times), capability of planning, thinking abstractly (or generalization) (each one 3 times), having judgment, perceiving relationships, using memory, comprehending language (two times) and finally being able to classify, calculation and imagination (each one once). Figure 1 shows the results of analysis of this group definition. In this figure, red bars demonstrate the characteristics that are common between all the groups that we have surveyed.
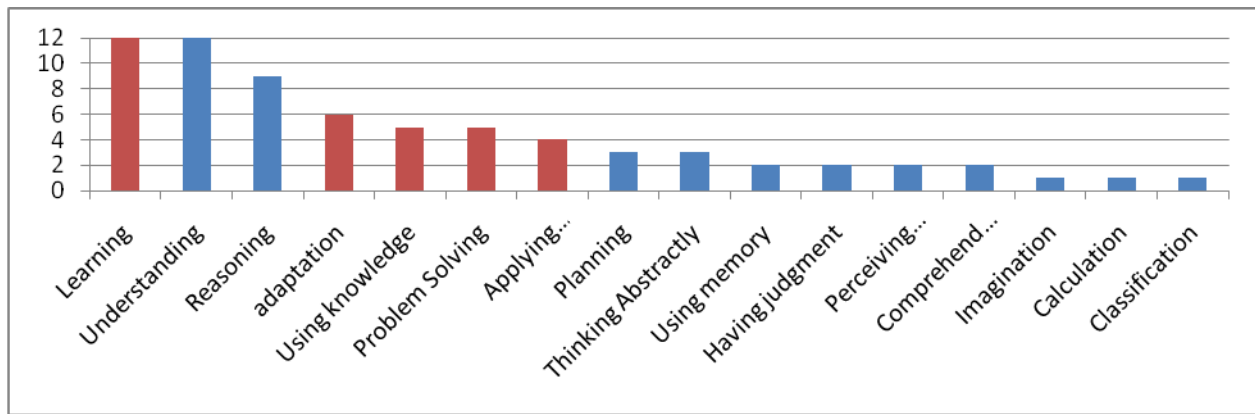
Figure1: Characteristics of Intelligence Based on Public Notion

Psychologists Definitions

This category contains 35 definitions from psychologists [6]. Taking into account these definitions in our survey helps us to understand elements of human intelligence according to psychologists and consider related attributes for computational intelligence.

We distinguish 23 issues that have been mentioned as features of humane intelligence in psychologists' definitions. They are ranked as the following according to their frequency in surveyed definitions: ability to adapt to the environment or new situations (8 times), learning, ability to solve problems and capability to acquire and apply knowledge (5 times each), thinking abstractly, having judgment, applying experience, imagination and perceiving relationship and generalization capability (each one 3 times), reasoning, perceptional recognition, capability to produce product, using memory (each one twice), and finally planning, quickness, flexibility, attention, pattern recognition, being educable, discrimination, sensation, cognitive ability (each one once). Figure 2 shows the results of analysis of this group's definitions. In this figure, red bars highlight the characteristics that are common between all the groups that we have surveyed.
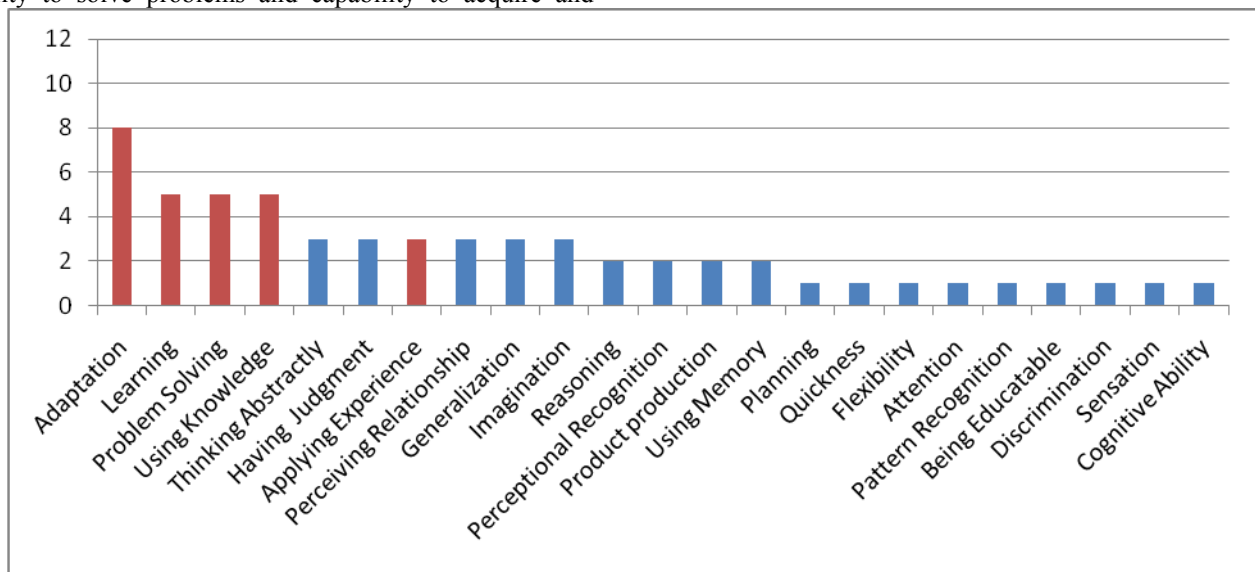

Figure2: Characteristics of Intelligence Based on Psychologists' Definitions

AI researchers Definitions

In this section, we analyze 18 definitions of intelligence from researches in artificial intelligence. The complete list of these definitions can be found in [6]. By reviewing these definitions, we identify that there are eight different topics as characteristics of intelligence which are: Goal-orientation (9 times), ability to adapt to the environment or new situations (4 times), learning (3 times), capability to solve problems (2 times), capability to acquire or apply knowledge (2 times) and applying experience and autonomy (each one once). Figure 3 shows the results of this analysis.
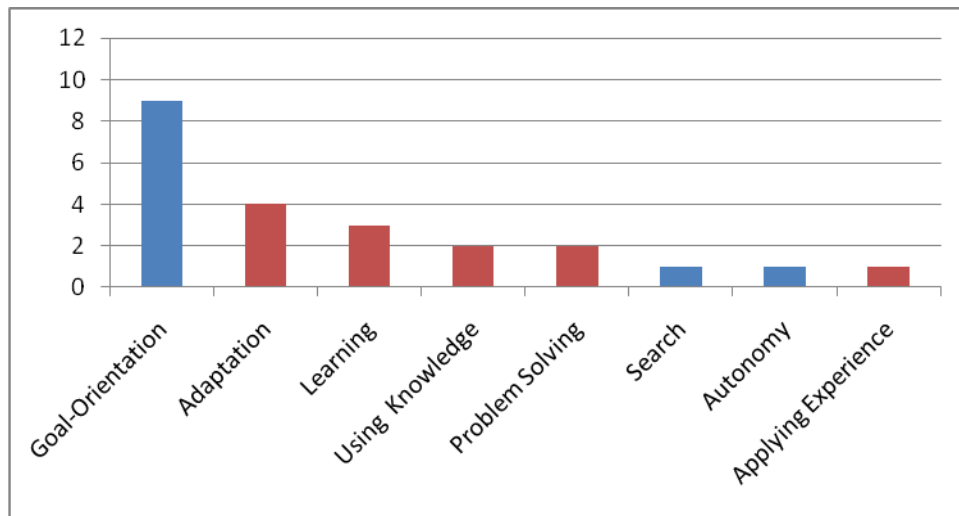
Figure3: Characteristics of Intelligence Based on AI Researchers' Definitions

Intelligence Characteristics in Computational Systems

By reviewing the results of analyzing definitions in different categories, strong similarities between many of these definitions quickly becomes obvious. This shows that there is an implicit agreement on some characteristics of intelligence. In addition, by taking into account their frequency of appearance, we conclude that some of them are more accepted as intelligence characteristic among experts than the others.

At the other hand, some of these features (especially features of intelligence in psychology and public definitions) are not suitable options for computational systems because they are not computable. In order to choose features of computational intelligence among distinguished set of characteristics, we omit these types of characteristics such as thinking, judgment, imagination, understanding, attention, product production, being educable, discrimination and understanding language. Because we are interested in intelligence as a behavior of software systems, we also ignore cognitive ability from our list. We also omit characteristics such as using memory or computational capabilities because they are the base of all computational systems. Otherwise, all computational systems would be intelligent and we are not interested in such a definition of intelligence.

After removing mentioned features, 16 characteristics remain in our list. To rank these features, we weight characteristics of different groups. We believe that characteristics that are mentioned by AI researchers are more important in computational intelligence than those that are considered in human intelligence. Therefore, AI features have more weight than features in public notions and psychology features get the least weight. The result of this approach is shown in Figure 4. In this figure, red bars demonstrate shared characteristics in all the groups of our survey.

According to this approach, features of computational intelligence are ranked as follow:

- Learning
- Adaption
- Goal-Orientation
- Using knowledge
- Problem Solving
- Reasoning
- Applying Experience
- Generalization
- Perceiving Relationships
- Planning
- Autonomy
- Perceptional Recognition
- Classification
- Quickness
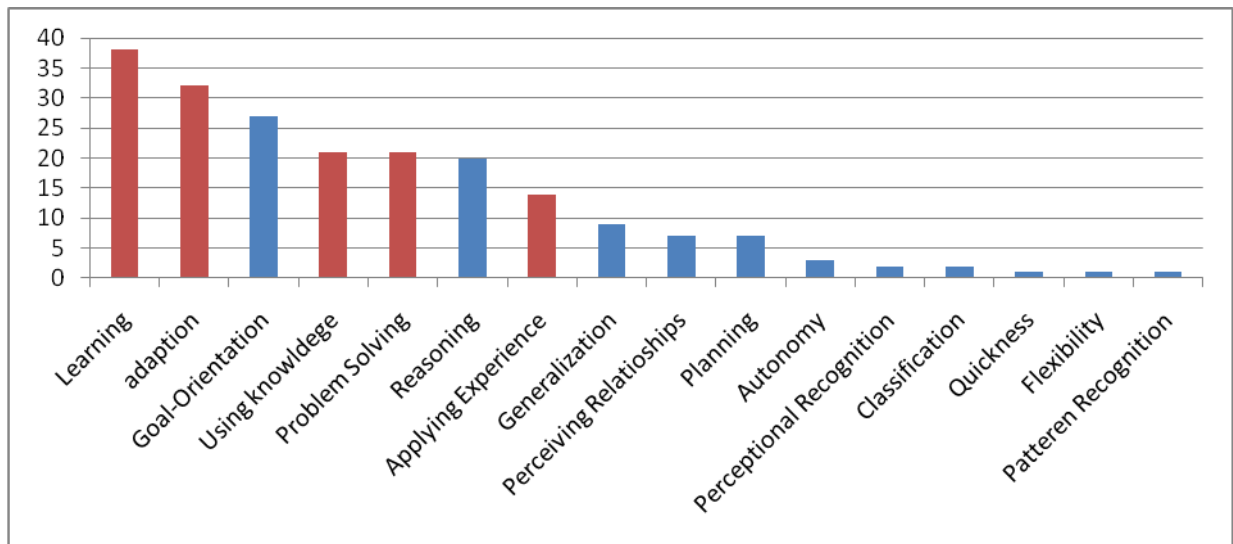- Flexibility
- Pattern Recognition

Figure4: Characteristics of Computational Intelligence

By examining these characteristic, we understand that these features are at different levels of abstractions. For example, some features are more general than the others, some of them are a subset of the others, and there are also some distinct features that refer to different capabilities of the system. To organize them, we divide these features into four categories. In this classification, intelligence is a feature of the system that improves non-functional requirements of the software system such as quickness and flexibility. To achieve this improvement, an intelligent system should be able to solve the problems in a goal-oriented manner. It also should be autonomous. In order to provide these general capabilities, intelligent systems need artificial intelligence capabilities such as reasoning, planning and learning that can be achieved through adaptation, pattern recognition, classification and applying experience. Intelligence of the system is founded on an infrastructure that contains knowledge and sensations or perceptions. Table 1 summarizes this classification.

Table1: Classification of Computational Intelligence Characteristics

Type	Characteristics
Non-Functional Requirements	Quickness, Flexibility
General Capabilities	Problem Solving, Goal Orientation, Autonomy
AI Techniques	Reasoning (Generalization), Planning, Learning (Adaptation, Pattern Recognition, Classification, Applying Experience,)
Infrastructures	Knowledge (Facts, Relationships), Perception (or Sensation)

Intelligence Characteristics and Non-Functional Requirements

When a capability is added to a software system, it improves software functionality. But there are some non-functional or quality requirements in the systems that should be taken into account during requirements engineering as well. In some cases, there are contradictions between these requirements. This means that by having some requirements in the system, we may lose or degrade the others. For example, by adding security features to the system, in general, more computations should be performed in the system. This can affect performance and efficiency of the system. In these cases, software engineer should choose a subset of requirements by considering the trade-off between requirements.

For looking at intelligence as a requirement of software systems, we need to analyze the side effects of intelligence and its characteristics on the other quality attributes of the system. For example, requirements engineer should pay attention to the side effects of considering learning requirement –as a feature of intelligence- on other quality attributes of the software system. Table 2 shows the relationship between learning and non-functional requirements. Characteristics of quality requirements in table 2 have been selected according to the classification of ISO 9126 [5]. In this table, "+" means that adding learning improves the non-functional characteristic. "-" means that learning potentially may decrease the sub-characteristic and "*" means that the relationship between learning and specified characteristic of non-functional requirement is neutral.

As this table shows, learning has a positive effect on characteristics of the system such as suitability, accuracy, interoperability, security, fault tolerance and adaptability.

But it has a negative relationship with efficiency and maintainability characteristics of system in general. This means that if quick response is a critical quality requirement and there is shortage of resources in the system, then adding learning to the intelligent requirements of the system should be done cautiously. The main reason is that learning utilizes extra time and resources of the system that may decrease its efficiency. Adding learning to the system also makes the code more complex, therefore changing the code or analyzing it when there is an error in the system becomes more complex and time consuming. Therefore, maintainability of the software decreases in general. But if adaptability is a required quality characteristic of the software system, adding learning as a requirement helps to attain an adaptable system.

Table2: Relationship between learning and quality requirements

CHARACTERISTIC	SUB-CHARACTERISTIC	Learning
Functionality	Suitability	+
	Accuracy	+
	Interoperability	+
	Security	+
	Compliance	*
Reliability	Maturity (hardware/software/data)	+
	Fault tolerance	+
	Recoverability (data, process, technology)	*
	Compliance	*
Usability	Understandability	*
	Learnability	*
	Operability	*
	Attractiveness	*
	Compliance	*
Efficiency	Time behavior	-
	Resource utilization	-
	Compliance	-
Maintainability	Analyzability	-
	Changeability	-
	Stability	-
	Testability	-
	Compliance	-
Portability	Adaptability	+
	Installability	*
	Co-existence	*
	Replaceability	*
	Compliance	*

Conclusion and Further Work

The aim of this research was identifying the main characteristics (or capabilities) of computational intelligence based on various definitions of intelligence. To achieve this goal, we analyzed more than 70 definitions of intelligence in various fields such as popular notion of intelligence, psychology and AI. According to the results of our survey, we distinguished 16 characteristics for computational intelligence.

This set can be used as a guideline (or reference) for eliciting and specifying expected capabilities (features) of intelligence system during requirement engineering. To develop an intelligent software (agent) system, first we should define intelligence requirements of the software according to the system or stakeholder's needs. As extracted characteristics are based on public notions of intelligence in addition to the AI experts' point of view, it can be considered as a common language between different stakeholders of the software such as developers and customers.

By specifying expected features during requirements engineering, later activities of software development such as analysis, architectural and detailed design and test of intelligence are based on a predefined set of capabilities. Furthermore, this set of requirements can be used as a basis for comparing intelligent agents in COTS (Component Of The Shelf) software development. To achieve this goal, intelligence requirements of the system (or agent) should be specified based on the proposed set of characteristics. At the other hand components that are developed should be defined according to this set as well. Having these preconditions, according to the intelligence requirements of the system (or agent), we can choose the most appropriate available component (or agent) for the system. For example, available components or agents are tagged according to their capabilities. In this case, if system needs an intelligent agent (component) that should be autonomous and being able to learn, we can choose the agent with these capabilities, according to the tags of available ones.

Our further works to extend our research are:
- Defining relationship between these features, in addition to the relationship with other non-functional requirements of software systems.
- Developing analysis patterns as the next activity of software development for these features such as learning analysis patterns[4]
- Defining validation and verification approaches for these features based on the existing methods for testing computational intelligence [7,8]

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