Back to the Basics – Redefining Information, Knowledge, Intelligence, and Artificial Intelligence Using Only the Adaptive Systems Theory

Vasile Coman

XCLSoft -- Principal
29 Middlesex Drive, Littleton, MA 01460
vcoman@xclsoft.com

Abstract

Decades ago, Alan Turing proposed a test to show if a machine has intelligence, a test that has yet to be replaced by a more comprehensive theory. The same test however, says nothing about what is intelligence. This paper proposes a definition based on a system ability to deal with uncertainty, which is the main attribute of our intelligence. It introduces a new adaptive system theory and the Viable Complex System (VCS), concept that is applied to organisms, social organizations, and to the design and architecture of IT systems. All VCSs share a dual structure built on two function types: *operations* (i.e. resource processing) and *change* (adaptability). A system adapts by learning from the interactions with environment on how to improve its chances to survive. All systems sharing common operations are part of a *realm*. Obviously, we may have systems which could live in two realms at the same time. In conclusion, we define *information* as the interaction between two similar VCSs, and *intelligence* as a property of adaptive systems which exist in the context of two realms (i.e. humans being biological organisms and members of the society). We extend the model to quantify intelligence through the use of a new term called *information density.* This concept associates complexity of the logic embedded in a message, especially the one related to changes, with the system ability to process that logic in its quest to survive. The more intelligent the system, the better it is at extracting information towards higher efficiency and higher viability. We are closing the paper with the presentation of two case studies from our practice that shows how this model can be applied in the IT when designing enterprise systems.

Hierarchies in Biology and Society

There is very little doubt that our ability to define intelligence lies in our success to capture the processes by which biological organisms are processing information received from their environment. Essential to these processes is that each organism has as its main existence goal the protection of its viability. As a result, many researchers like Ross Ashby (Ashby 1952), Stafford Beer (Beer, 1972), Jay Forrester (Forrester. 1961), and Maturana (Maturana and Varela, 1973) developed theories and models that tried to capture a system ability to survive in a changing environment.

Biological Organisms

In our theory of adaptive systems we start with a simple internal structure for biological organisms: the entire body is made out of cells, organized in a hierarchy which has on its lowest level the cells forming tissues, tissues forming organs, organs forming systems of organs, and systems of organs forming the entire body.

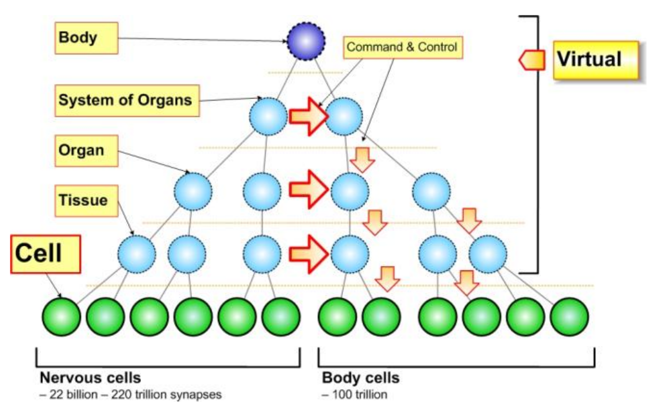

Figure 1. Physical structure – organisms have their cells organized in virtual hierarchies

From the information processing viewpoint the cells are of two types: **nervous** cells responsible for integrating the command and control functions and **normal** cells responsible with processing resources. Normal cells can be also split further into **sensor** cells and **motor** cells. Their numbers are in billions and trillions.

While human body has many other parts like organs or tissues, the only existing entities which are truly processing information and transforming nutritional resources are the cells. Otherwise said, they are the only ones having a true *operational* role, while the rest of entities (i.e. organs) are virtual structures made possible by the command and control function of the nervous system.

In this model, all cells are participating in two major flows. One is the **resource transformation flow**—it uses resources to extract and accumulate energy that runs the "operations" of the entire body—and the other one is the **information processing flow**—it uses information received from environment to protect and improve the efficiency of the resource transformation process, which is the basis of its existence. Within information flow, there are two smaller groups of normal cells playing an important role: *sensory* cells and *motor* cells. The first group is the primary *receiver* of information from environment; the second group *executes* instructions from the nervous system, once it is done processing.

Socio-economic Organizations

While it has far less complexity, an organization has the same type of hierarchical structure.

The top layer, where the CEO and a C-level team reside, helps with top decisions. Between the bottom *operational* layer—the value chain for resource transformation—and the C-level there are at least two more management layers: *developing a change* layer (i.e. product development) and *introducing operational changes* layer (i.e. change management). Similar to organisms, management layers are responsible only with maintaining organizational integrity and improve adaptability, without having a direct contribution to the value cycle.

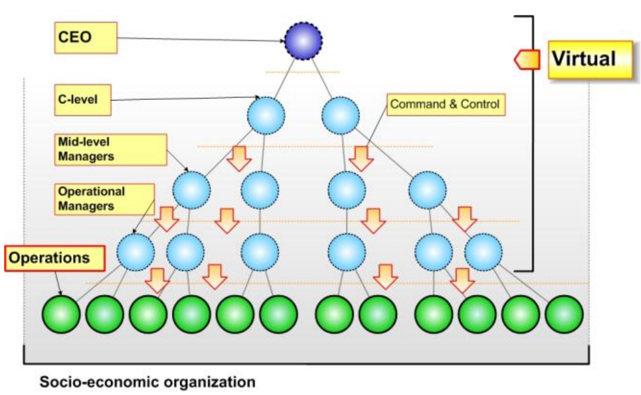

Figure 2. Physical structure—organizations share a similar structure with biological organisms

Ecosystems and society share a similar structure The similarities between biological organisms and organizations go beyond their internal structure. The environment in which they operate also follows a similar hierarchy. Ecosystems are built in layers based on the food chain cycle, while society is built on layers the financial accumulation cycle. At the top, all ecosystems have the most efficient predators, while lower *operational* layer uses plants and other unicellular organisms to carry out the primary transformation of resources. They take energy (i.e. solar, heat from deep ocean vents) and transform it into basic nutritional food, a process which is the starting point for the entire food chain.

In society, at the top level, government is the one responsible with ruling the society by issuing laws, enforcing them, and protecting its members. On the lowest layer, acting as the primary financial accumulation entity, is the family. Nevertheless, family plays a dual role, as a biological and a social unit. Between government and family there are two other layers which are playing an important role in controlling the resource transformation cycle: *businesses* and *investors*. Businesses are groups of society members which are assembled for higher efficiency, while investors are normally those providing financial resources. The entire socio-economic hierarchy closes the cycle between the top and the bottom layers by the democratic election of government officials. This is a process performed by all active members of a society.

Competition is the only process that drives the adaptability A group of similar biological organisms, with plenty of food available and living isolated in a static environment never needs to evolve. It could remain unchanged for millions of years. When environment changes and is populated by many other organisms, all competing for the same resources, there is always pressure to become more efficient at finding food, at finding a mate, or protect itself from predators.

In society, the same laws apply. A static society has very few chances to improve its organizations, while in a free market, open to competition, businesses and individuals have to continuously adjust to succeed.

Both the society and ecosystems are sharing a fundamental mechanism by which its individual members are competing. In nature, the main competition for individuals is driven by the *finding of a mate*. In society the same mechanism is the one that links the individual *consumer* to a *producer*.

One important rule that applies in the food chain is the independence between different layers in the food chain. While the cooperation may occur at the very small group scale, the majority have no privileged status, other than the position given to them by the place in the food chain. In modern societies, the trend is to ensure the same fairness between various layers in the financial accumulation cycle.

Socio-economic Realm and Biological Realm

From adaptability viewpoint we are aware of only two types of complex systems. One type is the biological organism living in an ecosystem. The other type is the socio-economic organizations that exist in our society. We call their environment the *biological realm*, and the ***socio-economic realm***. Both realms have in common a process of "energy" accumulation that is shared by all its members and creates the competitive background. In the biological realm organisms use their adaptability to increase their efficiency in *acquiring food*, while in the socio-economic realm all organizations target the *financial accumulation* as their main goal. The main driver that forces organizations to compete in the socio-economic realm is the increase in productivity. By using fewer resources to achieve the same product or deliver the same service, an organization can increase its customer base, which leads to higher financial accumulation and it improves its chances to survive.

Humans play a dual role Humans are the bridge that links the biological and the socio-economic realms. In one case, they are at the top of the food chain, while at the same time are the main entities forming organizations. This dual role is also the main source for their intelligence. Their nervous system need not only to process information related to their biological functions, but at the same time it is capable to address the challenges posed by living in a society, with its own set of rules.

Technology as the emerging realm In the last few centuries a new realm emerged in our society: the *technological realm*. However, the ability to process information was acquired only few decades ago. The new realm, represented by computers and robots, uses a different mechanism to process information, which is neither biological nor financial. However, its entities have no "energy" accumulation cycle driven by a resource transformation, and as a consequence are not self-sufficient. They are entirely dependent on the processes from the socio-economic realm. Nevertheless, technology is the key to improving our productivity, and it is also the basis of our hope to survive greater challenges as a society. This could range from cosmic object collisions to ever-adapting new viruses. The technology realm is also the domain in which we hope to develop robots based on AI frameworks, as the ultimate replacement for humans running operational tasks in our society.

What it is a Viable Complex System?

In the previous section we saw that both *organisms* and *organizations* are sharing a common hierarchical structure, one that drives operations and adaptability. Because their internal structure, organized around the resource transformation flow and the information flow, is driven by their need to survive, we call them **Viable Complex Systems**. These are systems capable to compete in an environment by continuously adapting their operations towards higher efficiency and better protection.

Because competition drives such environments, it makes all interactions unpredictable. As a result, adaptability is translated into the ability of a system to deal with *uncertainty*. By uncertain messages we understand those containing information that is not directly related to the resource transformation cycle, but it can be proven to be beneficial for its long term chances to survive.

In such system, the processing of an "uncertain" message always follows four steps. The first step is the *goal-oriented change phase,* in which information is evaluated for efficiency against an internal *performance model*. During the second step, called *change development phase*, information is used to decide on which path to take in modifying operations. The *developmental model* used reflects the ability to change. The third step is the *operational context change* phase, and uses a model that reflects the flexibility of existing operations. The last step, obviously is the *operational* phase, and uses as a model the resource transformation cycle. From this flow, we can draw two immediate conclusions: it is obvious that messages are fully processed only when their final destination is a change in system operations and the model complexity (linked to the abstraction level) increases bottom-up. Next, we analyze each of all four layers.

Operational Model

The least "uncertain" messages are those carrying simple operational instructions, such as "*buy a product.*" Because each system has embedded in its resource transformation cycle an *operational model*, the executions of such messages do not require any adaptability. However, systems can still use them to improve their operations by storing that information, and use historical data to calculate the risk of having to change in the near future.

A system *operational model* always revolves around the concept of a *lifecycle*, made out of *events*, that applies to the resource transformation. For instance, buying a product revolves around the lifecycle of an *order*. An organism *moving forward* (as an operational task) task is made out of many individual steps (i.e. events), which together can be assembled in a task lifecycle. An event is viewed in this case as a change in *state*.

Operational Context Change Model

Next step in complexity when comes to processing external messages are changes of *operational attributes* which can be considered part of the *operational context*. For instance, when comes to an order, the price is assumed to be a constant attribute during the entire transaction. However, there are situations when price needs to change. In that case all operations in progress have to account for it. The increased complexity comes from the need to process entities with old attributes and new attributes at the same time. It is very likely that during this *operational context lifecycle*, which is driven by the *operational context model*, the old and the new will need to be handled differently.

In biology, an example of such operational context change could be triggered by an external threat. In that case, the normal sequence of operational steps for an organism to *move forward* is changed into a new pattern to avoid the threat.

The development of a change model This is directly linked to the system ability to develop alternative scenarios for a change and pick the best one. While in society this model can be quickly identified as the product/service development functions, in biology it is less obvious at the individual organism level. However, it is the main mechanism that drives the natural selection in the process of evolution. To simplify the workflow we use for information processing, we consider that the development of a change is part of the goal-oriented model, because each scenario is evaluated for performance only.

Goal-oriented Change Model

While operational context changes can be triggered immediately by processing of external messages, goal-oriented changes have a far longer lifecycle. In biology, each small improvement towards better efficiency of fundamental processes could take millions of years. During this time, directions to improve those operational changes are vetted by tens of millions of years and countless experiments.

While in society, where cycles of change are far shorter, the processing of such a message needs to be done much faster, its complexity remains at the highest level. For instance, a business may receive an external message that can be interpreted as a signal of an impending economic crisis. In that case, its survival may depend on correctly translating that into a set of directions, and then decide on the sequence of operation context changes which could ensure their survival.

In conclusion, there are three basic models in use in an adaptive system: *goal-oriented change model*, *operational context change model*, and *operations*. However, these are not the only ones used in the battle to survive.

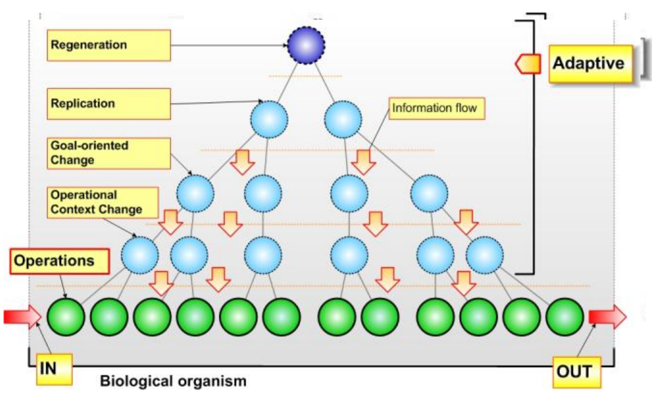

Figure 3. Logical structure— functions related to the organism adaptability are also organized in a hierarchy

Replications and regeneration

Once a biological organism is exhausting its capabilities to adapt based on the three types of basic change models, the Nature has two more aces in its sleeve. One of them is driven by the organism's ability to *replicate* itself when external conditions permit and is fundamental to all organisms. While this will not ensure the existence of the individual, it is a sure way to guarantee the survival of the species. The second process, *regeneration*, has the highest complexity, is in charge with restoring the basic functionality after a dramatic interaction with environment. Because of its complexity it applies only to very simple organisms (i.e. plants) or to simple processes (i.e. small wound).

In the socio-economic world, *replication* occurs in all societies, while the *regeneration* model is supported only in modern societies by the bankruptcy laws. They allow the maximum reuse of society resources even when operational models fail to survive.

Environmental and Dependent System models

Each message received from environment has two sides: a *physical* and a *logical* one. Processing the physical attributes is guided by Shannon's theory of information; processing the logic embedded is done by internal models. In the beginning, a received message is evaluated for its content if it is *operational* or *uncertain*. This evaluation matches an internal representation of the *environment model* to the embedded logic.

When an adaptive system is not at the bottom of the resource transformation cycle, after they process a message, they may forward it to a lower layer in the external hierarchy (i.e. a manufactured product is sold to a consumer, which depends on that product to improve its operations). This financial/resource exchange is always accompanied by an information exchange too. In this case, we say that consumer plays a role of a *dependent system*, and the business has to have internally a representation of its needs to establish this relationship.

The Viable Complex System Model

We call the sum of these models, which are helping to process external information messages and transform the resources the *Viable Complex System Model (VCSM)*.

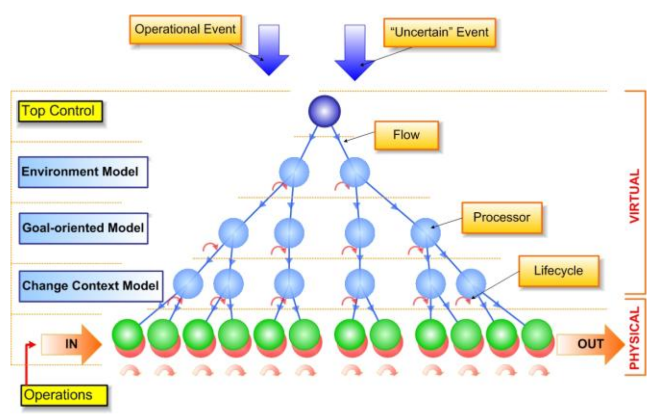

Figure 4. The VCSM combines the physical and the logical hierarchies into a single adaptive structure

Its internal hierarchical structure of physical entities and its hierarchy of controlling functions are linked together. Based on this definition, there are only two VCSs: *organisms* and *organizations*.

The Viable Complex System Model is predictive A fundamental attribute of adaptive/intelligent systems is their ability to anticipate future events and use it to their advantage. The VCSM revolves around two types of lifecycle: *resources* and various *context-based changes*. Because all lifecycles follows a blueprint of their events it is easy to anticipate what would happen next. Obviously, the more complex the external pattern, the more difficult is to use them to identify lifecycles and predict the next.

Socio-economic realm combines two Viable Complex System Models We, humans, are sharing within our existence the structure of two realms, one biological and one socio-economic. Obviously, the complexity of this interaction is what made us as intelligent as we are. However, this comes with a heavy price. While our internal biological adaptive system can manage the lifecycle of trillions of cells, we can barely track three different external events at the same time.

Interesting is that our society adopted many of the survival techniques found in Nature, such as maintaining the independence of socio-economic layers, or in creating an equal opportunity for all its members.

Information Density

Shannon's theory, developed in 1948, applies to the way information is encoded physically in a message, and is the basis for *signal digitization*. All existing IT systems, hardware and software follow its principles. However, the same theory doesn't apply to the processing of meaning/logic contained in a received message.

In the previous section we introduced a generic way to process the logic embedded in a message, and we linked them *uncertainty*. Uncovering the rules governing this link is directly influencing our ability to build AI frameworks.

In engineering, a successful approach is always to build systems from simple to complex. The same strategy, we need to apply to the processing of information messages. A system that adapts to external messages is always built bottom-up, starting with its operations (i.e. the resource transformation cycle).

The concept of *information density* associates a complexity scale to the content abstraction, based on the need to be interpreted by different models described in the VCSM. Their order follows the one found in the VCSM. At the highest level, is only of three types: *execution*, *operational context change*, and *performance*-related. Its calculation is inspired from *McCabe cyclomatic complexity* (McCabe 1976), which is a method to measure the complexity of a software program. *Information density* applied to messages is a *direct measure of the total number of linearly independent alternative paths across all three context layers reflecting the hierarchy of the transmitter lifecycle model*.

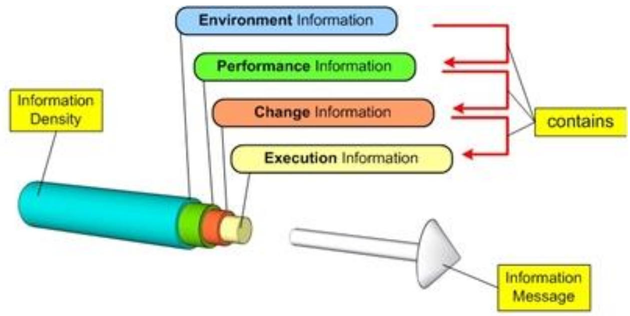

Figure 5. Information density links the message content (abstraction level) to the complexity of a system required for its processing

While this definition is less practical for external messages, it applies far better when they are forwarded between internal layers. However, in practice, the vast majority of existing engineered systems, IT or not, are able to process operational instructions only. Current approach makes adaptive systems very difficult to design.

Based on this definition, a message may have a multi-shell context-based structure. The *execution information* is found at the core of each message, while *context changes* are the next level up. On the next level is the information associated with system *performance* target, and the highest level of density is the information associated with abstract environmental activities, which could be only acknowledged. In the real world it is very likely a message may contain logic associated with more than one realm. In this case translation starts by filtering first the realm-related information, and only after this step is completed the real processing begins.

Information density pre-determines a message processing needs One of the most difficult tasks for a system that processes messages is to fully identify various meanings contained in the message logic and use it not only to execute the next task, but also to use it to improve all of its adaptive models. The most efficient way is to assess the message complexity from the time it receives it. This important step is helped by the concept of information density, concept which can be extended not only to organizations, but also to the design and the architecture of IT systems, including AI frameworks.

Adaptive systems and information density The same concept can be extended to systems too. We say that an adaptive system "*is performance/change/execution information density ready*" if it has internal models able to process messages with performance/change/execution density.

Examples

In the context of a profit organization that invests clients' money in buying shares, here are few examples of messages with different densities. "*Invest in buying shares and maximize the profit long term*" is a top message that builds the business model and is received from primary investors. They are the socio-economic controlling entity, external to the organization, and next higher in the hierarchy. This message can be translated by the C-level team into a strategic plan: "b*uy shares only from companies that experienced growth in the last two years*." It is *goal-oriented* and associates the performance of stock in the last two years with maximizing the profit. The last translation between management layers is an execution task: "*Buy IBM shares*." This last message is the result of translating the top message containing the business model directives into final operational tasks.

Information, Knowledge, and Intelligence

By using the VCSM as guide, we've seen that its internal structure is capable to adapt and anticipate what would happen next, even when external events are experienced for the first time. These are clearly attributes of intelligent systems. However, in our understanding, we do not consider biological organisms intelligent, with the exception of humans. Yet, the only difference between a human and any other biological organism is the creation of the new social realm. As a consequence, we propose three simple definitions for information, knowledge, and intelligence.

Information Definition

From the system viewpoint, *information is the mechanism by which two VCSs are interacting*. This interaction may take many forms, from visual and audio channels, etc. This definition, applies to both biological organisms and organizations.

Knowledge Definition

Each realm shares a common set of laws and operational processes, otherwise competition would not exist, and the adaptability will not be needed. *Knowledge is the sum of all these laws and rules associated to a realm*. From this definition we may say that a biological organism or a socio-economic organization is aware or "knowledgeable" of his environment if it has embedded in its layered structure a way to interpret same realm messages with higher information density.

Intelligence Definition

While biological organisms are able to have a complex interaction with their ecosystem, their activities are restricted to the biological realm. When an entity crosses another realm, as humans do, they develop the capability to interact and adapt their operational model to more than one realm. We call this ability *intelligence*. Obviously, the only entities we know that fit this definition are *humans* as individuals, and their *organizations*, as units of the socio-economic realm.

The AI

Based on this definition of intelligence, it is difficult to extract a simple way to label the AI.

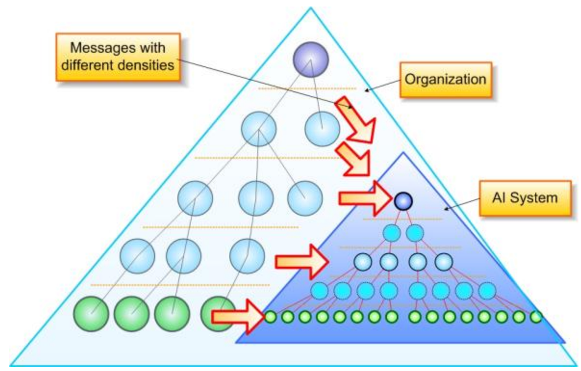

Figure 6. An AI system has to act as a replacement not only for operations, but also for management layers above

In practice, a system with AI capabilities it is very likely that it will play only a helper role for organizations from the socio-economic realm, as it is hard to envision having its own realm in which competition would drives further its adaptability. This is because an entity that belongs to a distinct realm has to be self-sufficient and compete based on a common process of "energy" accumulation.

In this light, AI-based systems have not only to automate existing operations in an organization, but also to act as replacements in management layers. All current systems, including the most advanced robots, are mainly restricting their processing to messages with operational context only.

Applying in practice

In a recent interview to the Scientific American, the famous enterprise architect Grady Booch pointed to a "dirty little secret" of today's software: most of the software-intensive systems have architecture that it's accidental, not intentional. This is true because we lack the theoretical foundations found in other engineering fields.

In our practice, we started years ago to use the VCSM concept on a smaller scale when designing modules for enterprise applications. One of the systems we helped build lately was an integrated order management. The challenge was to automate daily changes in price to orders in-progress at different locations. Our solution was to use context layers in the architecture and design.

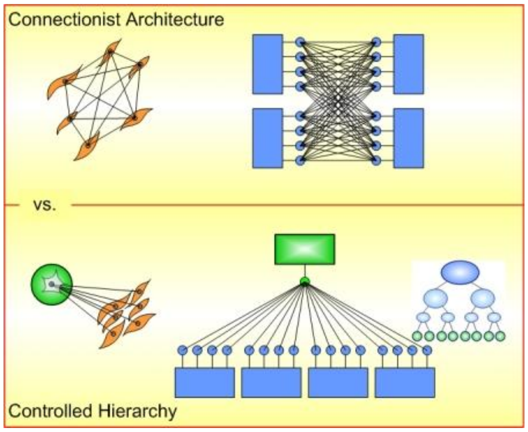

Figure 7. An hierarchical architecture, built on information and resource flows is many times more robust when comes to design changes

Another system we built recently was an integration platform for medical information residing at different agencies. The challenge was to translate data, stored by different processes, to a common business frame, while the identity of each individual patient was protected.

In both cases, the use of VCS principles resulted in huge cost savings and high quality implementation.

The main advantage of using the VCM to design IT systems is to translate the system architecture from a *connectionist* design to a *controlled hierarchy* built on operational changes. Because information flows inside a business is very unlikely to change, this design is very robust when comes to incorporate future requirements, the main cause of cost overruns, and project delays.

One other important benefit when using the VCSM is the use of the same hierarchical model for both adaptive systems and their environment. As a result, same solution can be applied regardless of the scale.

Conclusion

So far the focus for many initiatives, including the Biologically Inspired Cognitive Architecture field is to emulate the biology of the nervous system. Projects like DARPA's SyNAPSE (Systems of Neuromorphic Adaptive Plastic Scalable Electronics) program and IBM's Blue Brain Project had directly targeted to reverse engineer the brain by simulating as many as tens of thousands of neurons interacting. In both projects the neuron is used as the basic unit. Although this approach may achieve a biologically accurate architecture of individual neurons may have very little value when building their information processing model. Experiments have shown that nervous system has individual neurons performing more than one function at the same time (Yishai, Juergen, and Borst 2009). This ability makes it impossible to use the neuron as a unit in the development of an information-centric model of the brain because it is very difficult to match functions to physical entities. Other experiments endorsing this view have shown that C. elegans, a worm with only 302 neurons (Brenner 1974), has the ability to acquire complex learning patterns despite their simple structure. These facts show that adaptability doesn't need billions of neurons to be present.

There is an agreement in the AI field that "*as compared to biological systems, today's intelligent machines are less efficient by a factor of one million to one billion in real world, complex environments*" (DARPA/DSO SyNAPSE). John McCarthy, the researcher which coined the AI term back in 50s, said in a recent interview that "*simulating higher functions of the brain*" it is still a "*question of basic ideas*" and not "*the lack of machine capacity*" (McCarthy 2006). Our hope is that the VCSM concept fill that role.

Acknowledgement

XCLSoft is a company dedicated to advancing the theory of adaptive systems and its practical applications in engineering, especially in the IT field.

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