INTERNATIONAL CONFERENCE ON ENGINEERING AND PRODUCT DESIGN EDUCATION
6 & 7 SEPTEMBER 2012, ARTESIS UNIVERSITY COLLEGE, ANTWERP, BELGIUM

# PRODUCT DEVELOPMENT EDUCATION - CONCEPTUAL MODELLING, KNOWLEDGE INTEGRATION AND METACOGNITION

**Tero JUUTI**[1], **Timo LEHTONEN**[1] **and Kaisu RÄTTYÄ**[2]
[1]Tampere University of Technology
[2] University of Eastern Finland

## ABSTRACT

This paper concentrates on building up a model of how existing knowledge can be learned and applied successfully in new product development. Our case based research draws upon constructivist learning theory, on conceptual change theory combined with findings in cognitive neuroscience. Describing the cases and theoretical development we build the model that focuses on existing knowledge as network, knowledge building, knowledge representation and procedural knowledge. We have achieved better learning result by teaching the subject as visualised elements and relationships between the elements as a model. The simulation game involves multiple memory types and facilitates knowledge integration when the learning process consists of doing, time for reflecting, discussion on the concepts and their meanings. When the students can apply knowledge based on experiences within minutes the neural connections strengthen. Time needs to be reserved also for metacognitive activities, such as making conscious choices on problem solving rather than using rote learning and procedural skills.

*Keywords: Systemic knowledge, metacognitive skills, concept mapping, simulation games*

## 1 MOTIVATION

The education of new product development in Tampere University of Technology (TUT) has been based on the behavioural learning theory. The main courses for 3rd and 4th year students cover product development processes, new product development project management and product structuring i.e. standardisation, modularisation and variability. We have observed in our courses, based on the discussions, exams and exercises that the information and knowledge we teach appears in many forms in the students' minds and the students reasoning logic and explanations differs from ours. This is visible for example in student exam papers.

The foundation in constructivist learning theory is "*knowledge is not an entity which can be simply transferred from those who have to those who don't "[1]*. This resonates quite well with our experiences with the students. Constructivism states that learning is an active, contextualized process of constructing knowledge rather than acquiring it [1]. In other words, learning by doing could be more effective way of learning than attending lectures.

The industry has similar feedback for us. TUT has extensive and long term collaboration since 1980´s with industry. The feedback from over 20 managers is that the students are missing some skills needed in their profession. The more detailed discussions revealed the managers belief the skills can be learned only at real work during several years i.e. learning by doing. These skills are perceived as tacit knowledge and difficult to teach at university. Based on our initial findings, on the feedback from industry and literature, our research questions are

1) *How the student can learn existing systemic knowledge and*
2) *How the student is able to apply existing knowledge successfully?*

Our focus is with the following skills; [adapted from 2]: 1) Modelling conceptual abstractions; Ability to define and model the entities or elements of the system, important relationships, interactions and interfaces among elements, 2) Knowledge Integration by linking knowledge together and identifying the structure of knowledge, 3) Self-Awareness and Metacognition; The extent of one's abilities, and one's responsibility for self-improvement to use strengths, overcome weaknesses and making conscious choices between different learning, problem solving and engineering design strategies.

Our intent is to elaborate how to teach the needed skill in an effective manner. The approach is based on synthesis made of several learning theories covering the learning situation, facilities, teacher, student and the group of students. Some of the building blocks are from *constructivistic learning theories*. We focus on the *conceptual change* capability of the student. The synthesis also consist of relevant issues found in *cognitive neuroscience* i.e. how brains function and e.g. what is the role of memorizing when applying knowledge in different context.

## 2 RESEARCH APPROACH

Our research strategy is based on Yins´ Case Based Research method [3] and is aligned with Design Research Methodology by Blessing et al. [4]. The research process begins by identifying and specifying a problem to be solved. The next phase is to choose most relevant theories within assumptions. Then the model describing the problem at hand is created and plans are made to validate the model using real life cases. Valid conclusions can be made when the results from the cases correspond to the model. Currently the model is under construction, some cases are done and analysed and further cases at Tampere University of Technology are under planning.

## 3 THEORETICAL BACKGROUND

We build our study on constructivist learning theory, on conceptual change theory originating from philosophy and history of science and on the cognitive neuroscience that is combination of cognitive psychology and biomedical field of study on nervous system. ”The knowledge is constructed in the mind of the learner” [5] based on personal experiences and hypotheses of the environment. Learners keep testing these hypotheses through social negotiation. Each person has a different interpretation and construction of knowledge process. The learner is not a tabula rasa but brings own past experiences and cultural factors to a situation. New information is linked to prior knowledge, thus mental representations are subjective [6]. Connectionist models of learning and development characteristically generate progress from a conceptually impoverished to a conceptually richer system [7].

The **conceptual change theory** postulates that knowledge is modelled in brain as elements and relations. Conceptual change means that student needs to re-evaluate certain concept and its relations to other elements as learning takes place. The theory consists of two competing theoretical perspectives about knowledge structure coherence. These perspectives can be described as (A) *knowledge-as-theory* and (B) *knowledge-as-elements* [8]. These two perspectives are summarized in following questions: “Is a student’s knowledge most accurately represented as a coherent unified framework of theory-like character?”[9]. or: “Is a student’s knowledge more aptly considered as ecology of quasi-independent elements [10]. Both perspectives agree on the claim that conceptual change is time consuming process. They disagree how the conceptual change takes place i.e. in revolutionary (A) or evolutionary (B) manner. The theory contributes to this study by indicating the importance of learners existing experiences and naïve constructions. If the domain is familiar to the student the “knowledge as elements” teaching perspective is recommended. In our context there are students with existing naïve models and students with no previous experiences and concepts regarding this matter. Therefore we assume both perspectives are relevant and needed.

Strike and Posner [11] advocate that that the basic problem of understanding cognitive development is to understand *how the components of an individual’s conceptual ecology interact and develop and how the conceptual ecology interacts with experience*. From a **conceptual ecology** perspective, the essential ideas, ontological categories, and epistemological beliefs influence a learner’s interactions with new ideas and problems. Misconceptions are therefore not only incorrect beliefs; misconceptions organize and constrain learning in a manner similar to paradigms in science. Former conceptions are highly resistant to change because concepts are not independent from the other cognitive artefacts. Some concepts are attached to others and they generate thoughts and perceptions. Because of this web-based relationship between concepts, a revision to a concept requires revisions to others [8]. For education this means that when using general words, such as architecture, component, design, process, we need to be very specific and make time to discuss with the students on the meanings and relations of these word in product development context.

Cognitive scientists have largely focused on two broad types of knowledge, **declarative and procedural** [12]. This distinction has been useful in rule-based computer modelling of cognitive processes, but its application to education and knowledge creation is questionable [13]. From a pragmatic standpoint, a more useful distinction is between knowledge about and knowledge of something [14]. **Knowledge about** consist of the declarative knowledge you can retrieve when requested to state what you know about sailing. Such knowledge could be conveniently and adequately represented in a concept net. **Knowledge of** sailing, however, implies an ability to do or to participate in the activity of sailing. It consists of both procedural knowledge (e.g., knowing how to navigate) and declarative knowledge that would be drawn on when engaged in the activity of sailing (e.g., knowledge of the boat hull impact on compass bearing). It entails not only knowledge that can be explicitly represented or demonstrated, but also implicit or intuitive knowledge that is not manifested directly but must be deduced. Knowledge of is activated when a need for it is encountered in action. Whereas knowledge about is approximately equivalent to declarative knowledge, knowledge of is a much richer concept than procedural knowledge [14].

Kilpatrick [15] has introduced **strategic knowledge** as one important metacognitive skill in learning mathematics. The learner needs also to consciously consider which procedure to use and in which situation; otherwise student is relying on the existing procedures that may not fit to the situation. An important notion is that the procedural knowledge provides fast reactions triggered by perception. While the reaction time is fast the correctness or validity is not considered at all [16]. This might be reasonable in some everyday situations. It has enormous effect on design results if this approach is allowed in product development project where hundreds or thousands decisions are made and fast reactions are preferred rather consideration and reasoning. Rock [17] has illustrated similar cognitive function as **hardwiring**. The brain is able to identify repetitive activities and intentionally aims to code them to be automated. Something in the situation triggers automated reaction and deduction or conscious thinking is not needed. This is a cognitive function found in cognitive neuroscience having effect on conscious actions.

**Cognitive neuroscience** [18] is a combination of cognitive psychology and neuroscience. Cognitive psychology studies cognitive, higher human brain functions i.e. perception, attention, learning and memory, emotions, reasoning, decision making, problem solving. The unconscious, automatic reflexes are not studied in cognitive psychology. Neuroscience focuses how the nervous systems of humans are organised and how they function. The relevant issues found in cognitive neuroscience for us are that what is the role of **memorizing** and **retrieval** functions when applying knowledge in different context. The studies show that **emotions and mood** has an effect on memorizing and on retrieving memorised cognitive elements [18]. The studies indicate also that not only the procedural skills can be automates but also the cognitive functions. We can take for example two cognitive functions, perception and sub function of memorising, called as priming. Their combination results as perceiving data familiar from previous experiences and memorizing those. This inhibits perceiving what else is happening at the situation and memory retrieval is very difficult [18]. This calls more **conscious decisions** from us during the educations **on** where we want to put the students **focus**.

The research [18] shows that working memory is "faster" i.e. it is able to learn and memorise new cognitive elements quickly, within minutes. Then again, the long term memory requires cognitive function called consolidation to be able memorize new cognitive elements and thus is much slower. **Consolidation** means that the old and new cognitive elements in the same mental map are considered as whole and conflicting relations or meanings are removed. This results in concise and logical concept map [19]. Consolidation takes from hours to days and for learning new cognitive elements and creating memorisable concept map takes more than couple of hours.

When knowledge building fails, it is usually because of a failure to deal with problems that are valid for students and that bring forth real ideas from them. Instead of connecting to the larger world of knowledge creation, the tasks or problems are mere drills and are perceived by the students as such. [7] Based on Kilpatrick [15] we need also train the strategic metacognitive skills. The student needs to reflect on where the focus is, which premises are relevant and valid, which alternative tools or solutions there are available etc. This will increase the ability tube present and to make more conscious choices rather than automated procedures.

## 4 CASE ANALYSIS

We have used simulation games during years 2005-2012 in the modularisation-course. The simulation games are designed for teams from five to nine members. The first simulation game, called 18-Wheeler, was originally developed for Nokia corporation internal education [20]. The simulation has 5 phases and students repeat the same tasks in different phases 3 times. The duration of each phase is about 1 hour and the reflecting takes place only in the last phase. The learning outcome has been satisfactory but the maximum amount of participants, 30 persons, was not enough when the amount of students in the course reached over 100 persons. This lead to development of another simulation game – Apollo 13. The similarities to the 18 Wheeler are that the duration is 6 hours, the work is done in teams and Lego building blocks are used in both simulation games. However, Apollo 13 has some new features such as Kolb´s [21] learning model is used 6 times in 8 different phases. This increases the amount of repetition, shortens the time from doing to reflecting down to 20-30 minutes. This approach links stronger the meaning of particular concept, such as *Architecture* or *Interface*, to particular episode in the simulation. This facilitates connections between declarative memory and episodic memory. In addition the physical building uses kinaesthetic, motor skills, stored in procedural memory and creates connections between three different memory types. The preliminary analysis indicates that the shorter time from doing to reflecting and applying the new knowledge improves learning. Student teams are also able to discuss with educators in each phase during the reflecting and this assists students to construct connections between a concept, an episode and a motor task. They need to plan how they perform the next phase, what they do similarly and what they do differently and this forces them to apply gained knowledge at once. Comparing to 18 Wheeler the Apollo 13 seems to facilitate the learning more efficiently.

## 5 SYNTHESIS – THE MODEL

Our model is based on three assumptions; 1) the existing knowledge is network like map, 2) systemic thinking is needed when designing large artefacts and 3) automated cognitive functions partly serve the problems solving tasks. We use the term existing knowledge meaning such information that is commonly known in the society. For example, the industrial experience is that if the main supplier changes during the new product development process the product architecture is opt to changes. This change potentially has an effect on the value creation options in customer use. The key learning point in this case is that product architecture is not optimised only from the products functionality point of view.

### 5.1 What is existing systemic knowledge?

We build the definition on [22] *"knowledge is a network of strongly connected cognitive elements that represent the generic concepts in memory"*. In addition set of concepts with relations between them defining how the concepts relate to each other are required. The relations; dependencies and dispositions carry the meaning of the relation. The relation can link to another concept map consisting of concepts and relations. When the domain area is limited all relevant knowledge can be visualised in one concept map. In most cases there is need to share knowledge in wide domain area and then the knowledge is distributed in multiple concept maps. The connection between concept and relation enables us also consider when this particular relation is valid. The relation and the concept map can be valid under certain circumstances and this is also vital knowledge to share. As some of the students have experiences in the designing domain they also express questions and opinions on the relations. The discussion on these facilitates understanding on the circumstances and the validity of relations between concepts.

### 5.2 How the knowledge and the knowledge representation is created?

The second part of the synthesis addresses how the knowledge is created. The first step is to identify new cognitive element, a concept. One way to identify new concepts is to list items. In Apollo 13 student are collided with new concepts by preplanned episodes that represent particular phenomena such as interchangeable modules. The items in the list are concepts but their relation to the topic and to the other items remains unclear. The meaning of the concept is built by establishing relations to other concepts. The relations help for example the classification of different cognitive elements. The relations carry the meaning of the concept in particular context. As the relations are defined the next step is to evaluate which relations are the most important. This enables us to analyse, create expert systems and predict what could be the result based on the knowledge. This new knowledge is accommodated and assimilated to the existing concept maps by the student [19 22]. As long as the existing conceptual schema works and feels functional enough the student does not have the need to change the schema or mental model. The learner may make minor modifications, accommodation to the conceptual schema, if the student is dissatisfied with the schema.

### 5.3 How to apply existing knowledge successfully with and without procedural knowledge?

The intention is to enable student to construct at least as valuable knowledge as we have. As the student applies his own knowledge the outcome is better than retrieving and executing our model from memory without thinking using procedural knowledge. Procedural knowledge is used when fast reaction is needed and the hind side is that there is no time to consider whether this procedure is valid in that particular situation.

## 6 CONCLUSIONS

This paper elaborates the synthesis based on several research fields. The synthesis describes how students can learn existing knowledge and how they can apply it successfully. The research fields are explained to increase understanding on the disciplines that were used to build up the synthesis.

We propose that the subject being taught is visualised as elements and relationships between the elements as a model. The model is constructed gradually, element by element so that the student is able to learn the logic and has possibility to modify and improve one's cognitive elements, relations and meanings. The visualised model serves as external memory and frees working memory. When the learning process provides time needed for reflection the students learn also to use their metacognitive skills in addition to procedural skills.

## 7 DISCUSSION

The literature used in this study emphasises the role of existing knowledge and experience having effect on the teaching approach. We see that using simulation games creates common and shared experiences to the students. This enables us to introduce new concepts with particular meaning in product development context. It also serves as a set of practical examples when introducing the overall concept map. When we approach learning from "knowledge as theory" perspective we start by presenting the overall view on the topic. It covers the whole topic with the assumptions and conclusions. We avoid using plain lists of elements; we can start with them and continue by building concept map. When there are more elements that working memory can contain (5-9 elements) we chunk the topic in smaller entities. If we use metacognitive tools as thinking aids such as schemes, analogies and metaphors, we consider how well they fit to the purpose. When students create misconceptions based on the analogies, the learning task (and teaching task) is much more complex. The end result of the whole training needs to be created by the students using their own mental models. As the problems in industry are open-ended there are many alternative ways to approach the issue. We think the utility of the concept map is of more importance than similarity to our own concept maps. We need to plan the time needed for personal and group reflection to facilitate creation of cognitive elements and to enable students to use strategic metacognitive skills. We notice that in research the aim of explanatory model is to be such that another person is also able to use the same model and apply it with success. This is not the case in learning; our goal is that the student is able to solve problems using his own concept map, not anyone else's. In our courses we mainly focus on knowledge about (etc. lists, rote learning, and simple procedural ability) and in future will focus also on deduced knowledge when engaged in problem solving by using problem based learning.

## REFERENCES

[1] Lochhead, J. *New horizons in educational development*. In: Review of Research in Education, 1985 (American Educational Research Association, Washington, D.C).

[2] Crawley, E., Malmqvist, J., Östlund, S., Brodeur, D., *Rethinking Engineering Education: The CDIO Approach*, 2010, Springer.

[3] Yin, R. K. *Case Study Research*, 1994, 2009 (Sage publications Newbury Park, CA).

[4] Blessing, L.T.M., Chakrabarti, A. *DRM, a Design Research Methodology*, 2009 (Springer London).

[5] Bodner, G. 1986. Constructivism: A theory of knowledge. *Journal of Chemical Education*, 63(10), 873-878.

[6] Tynjälä, P. *Oppiminen tiedon rakentamisena. Konstruktivistisen oppimiskäsityksen perusteita,* 2000 (Tammi, Helsinki).

[7] Scardamalia, M., & Bereiter, C. 2006. Knowledge building: Theory, pedagogy, and technology. In K. Sawyer (Ed.), *Cambridge Handbook of the Learning Sciences* pp. 97-118 (Cambridge University Press, New York).

[8] Özdemir, G., Clark, D.B., ”An Overview of Conceptual Change Theories”, in: *Eurasia Journal of Mathematics, Science & Technology Education*, 2007, 3(4), 351-361, 2007 by Moment, E-ISSN: 1305-8223,

[9] Chi, M., Roscoe, R., Limón, M., Mason, L., The Processes and Challenges of Conceptual Change - Reconsidering Conceptual Change. In: *Issues in Theory and Practice*, 2002 Springer Netherlands, Pages 3-27, ISBN 978-1-4020-0494-0, http://dx.doi.org/10.1007/0-306-47637-1_1

[10] diSessa, A.A., Gillespie, N.M., Esterly, J.B., Coherence versus fragmentation in the development of the concept of force,. In: *Cognitive Science*, Volume 28, Issue 6, November–December 2004, Pages 843-900, ISSN 0364-0213, 10.1016/j.cogsci.2004.05.003.

[11] Posner, G. J., Strike, K. A., Hewson, P. W. and Gertzog, W. A. 1982, Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education*, 66: 211–227. doi: 10.1002/sce.3730660207

[12] Anderson, J.R. *Cognitive psychology and its implications*, 2004 (Worth Publishers, 5 Ed.)

[13] Bereiter, C. *Education and mind in the knowledge age*, 2002. (Lawrence Erlbaum Associates, Mahwah, NJ)

[14] Scardamalia, M., & Bereiter, C. 2006. Knowledge building: Theory, pedagogy, and technology. In K. Sawyer (Ed.), *Cambridge Handbook of the Learning Sciences* pp. 97-118. (Cambridge University Press, New York).

[15] Kilpatrick, J., Swafford, J., & Findell, B. (Eds.). *Adding it up: Helping children learn mathematics,* 2001 (National Academies Press, Washington, DC)

[16] Andrew E. Welchman, James Stanley, Malte R. Schomers, R. Chris Miall, and Heinrich H. Bülthoff. The quick and the dead: when reaction beats intention, 2010: rspb.2009.2123v1-rspb20092123.

[17] Rock, D. *Quiet Leadership: Six Steps to Transforming Performance at Work*, 2007 (HarperCollins).

[18] Purves, D., Brannon E.M., Cabeza R., Huettel S.A., LaBar K.S., Platt M.L., Woldorff M. *Principles of cognitive neuroscience*, 2008 (Sinauer Associates, Sunderland Massachusetts)

[19] Novak, J. D. *Learning, creating, and using knowledge: Concept maps as facilitative tools in schools and corporation,1998 (*Lawrence Erlbaum Associates, Mahwah, NJ)

[20] Juuti, T. *Design Management of Products with Variability and Commonality*, 2008 (Tampere University of Technology, http://urn.fi/URN:NBN:fi:tty-200903021019)

[21] Kolb, D. A. *The experiential learning: Experience as the source of learning and development.* 1984 (Prentice-Hall, NJ).

[22] Strauss, C., and Quinn, N. *A cognitive theory of cultural meaning,* 1997 (Cambridge University Press, Cambridge, UK).