FATHOM: TEL environment to develop divergent and convergent thinking skills in software design

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***Abstract*— Divergent and convergent (D&C) thinking skills are important in solving software design problems. Divergent thinking involves processes like understanding the problem from multiple perspectives and generating multiple solutions to a problem. While, convergent thinking is evaluating and selecting the solution based on the criteria and constraints. These skills are important in software design process for better design outcomes. Studies have shown that students lack the abilities to apply these skills spontaneously to solve design problem. In this paper, we present the design of a Technology Enhanced Learning (TEL) environment with metacognitive support to foster D&C thinking skills in engineering students. The scaffolds are characterized in the form of prompts, examples, simulations, and D & C thinking tools to trigger D & C thinking during real life design problem solving in data structures. A study was conducted with second year computer engineering students to find the effectiveness of the metacognitive and cognitive prompts in doing the D & C thinking activities. The results show that design features have helped students perform the activities effectively. These results are supported with student's perception survey and student interviews.**

Keywords—divergent thinking; convergent thinking; software design; cognitive prompts; metacognitive prompts;

I. INTRODUCTION

Divergent and Convergent (D&C) thinking skills are elementary cognitive processes to solve design problems [1]. Design problems are ill-structured in which the goals may not be clearly specified. Such problems may be related to real life problems, possess multiple solutions and one has to identify criteria to evaluate solutions and select the optimal solution based on the constraints identified in the problem[2]. The example of software design problem is, *"Design a software system for a bank to store and retrieve customers' account details quickly"*.

During the process of solving such problems, divergent thinking is looking at the problem from multiple perspectives and generating multiple solutions. While, convergent thinking is evaluating and selecting the solution based on the criteria and constraints. These skills when applied to design problem solving process, results in better design outcomes [3,4].

The software design problem solving broadly consists of three phases- problem analysis, designing the solution and implementation. The process of applying divergent to convergent thinking in first phase of problem solving allows one to understand the problem from perspectives of stakeholders and entities and converge towards problem representation. Similarly in second and third phase, the process of exploring the problem solution space by thinking of all possible solutions and evaluating and selecting the solution based on the criteria will help in designing better solution and justification [5].

Students tend to jump to solving problem without understanding the system from multiple perspectives and explicitly generating solutions [5,7]. Studies have shown that scaffolding mechanism in the form of prompts is effective in developing thinking skills in problem solving [6,7].

The aim of our research is to design a learning environment for the teaching and learning of D & C thinking skills. In this paper, we present the design of TEL Environment for D & C thinking skill, named as *Fathom*. Fathom is a guided learning environment, with scaffolds characterized in the form of prompts, examples, simulations, and D & C thinking tools to trigger D & C thinking during real life design problem solving in data structures. A study was conducted with second year Computer Engineering students to investigate the research question- *"How effective is Fathom in learning divergent and convergent thinking skills?"*

In next section, D & C thinking skills are explained in the context of software design followed by teaching and learning of these skills. Then the design of the TEL environment for D & C thinking skills (Fathom) is discussed followed by study, discussion and conclusion.

II. DIVERGENT AND CONVERGENT THINKING SKILLS

1. Divergent and Convergent Thinking in software Design

Software design process is used to design a software system to solve complex real life problems. Research suggests that integrating D & C thinking in each phase of design process- analysis, design and implementation, improves the quality of the design [1,3,4]. Based on the literature on engineering design [4], design thinking [8], and creative thinking [11] we had identified the D & C thinking processes in each phase of software design [5] as shown in figure 1. In this paper, we have addressed D & C thinking for first two phases- problem analysis and design and third phase implementation is out of scope of discussion.

The major challenge is the teaching and learning of the D & C thinking skills in each phase of problem solving given in figure 1. In next section we have discussed how we have

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addressed this problem. Based on the literature on problem solving, first we have identified the sub-skills involved in D & C thinking. Next, we identified the scaffolding mechanism used for teaching and learning of these skills for novice learners.

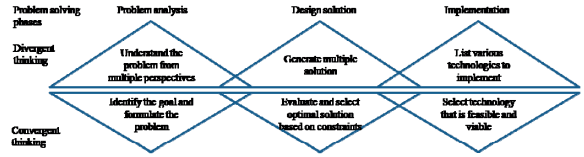

Fig. 1. Software design problem solving process integrated with divergent and convergent thinking skills.

2. *Identification of subskills in Divergent and Convergent Thinking Skills*

In the context of ill-structured and technical problem solving, cognitive skill is an ability to solve a problem efficiently using domain specific knowledge. Metacognitive skills are higher level skills like- identifying problem, problem representation based on goal, monitoring and evaluating solutions and making justifications [9, 7]. Based on the cognitive and metacognitive processes and tools used by experts in solving ill-structured problem, the sub-skills of D & C thinking skills for first two phases shown are identified and given in table 1.

3. *Teaching and learning of Divergent and Convergent thinking skills in sofware Design*

It is empirically proven that the cognitive and metacognitive prompts are effective in scaffolding students thinking skills in problem solving to achieve better solutions or learning outcomes. Cognitive prompts directly support a student's processing of domain specific information. Metacognitive prompts support student's monitoring and control of their cognition through metacognitive and reflective activities like identifying goal, evaluation of solutions, etc [6, 7].

Research shows that student with low prior knowledge on metacognitive skills are not able to effectively perform the activity as prompted [6,5]. Thus to help students in effectively performing the activity- i. The metacognitive activities should be explained in detail, demonstrated or practiced before the learning session, ii. The metacognitive prompts cause additional cognitive load which could be compensated by training and flexible knowledge base and iii. Provide feedback on adequate use of prompted strategy to improve the quality[6].

III. DESIGN OF TEL ENVIRONMENT TO DEVELOP DIVERGENT AND CONVERGENT THINKING

Based on the principles of effective metacognitive support for novice learners, a Technology Enhanced Learning Environment for Divergent and Convergent Thinking named *Fathom*, was designed and developed. The design decisions are based on the fact that students are naive in design problem solving and lack the ability to spontaneously apply D & C thinking skills in solving design problems.

The design features for training D & C thinking skills identified in table 1, are discussed in this section.

1. *Learning Activities in Fathom*

The learning environment systematically guides students through three steps- motivation, posing real-life design problem, problem solving phases with D & C thinking activities.

1.1 Motivation

The students are introduced to the importance of the D & C thinking skills, learning outcomes and problem solving phases, before proceeding to problem solving. This design decision is based on the design principle that the application and usefulness of the metacognitive strategies have to be explained for effective instruction [6].

1.2 Real-life design problem in data structure is posed

Later, the open problem is shown with simulation of the bank scenario to show different operations- withdraw, deposit, check_balance, performed in the bank between customer and bank teller as shown in figure 2. The simulation is efficient in modeling real system, and help students in experiencing the problem and creating a mental model of the same.

TABLE I. SUB-SKILLS FOR DIVERGENT AND CONVERGENT THINKING SKILLS IDENTIFIED BASED ON PROCESSES AND TOOLS USED BY EXPERTS

Processes and tools used by experts in each step of problem solving	**Sub skills**
	Phase 1.Problem Analysis
Problem identification	Divergent thinking- Look at the problem from multiple perspectives
To identify problem, experts create the mental model of a system to show the entities, its properties and interactions among them [9, 6] For example, in troubleshooting, experts create a more complex and accurate mental model of the system.	1 Identify the entities 2 Identify the properties 3 Identify the interconnections 4. Draw the mental model to represent entities, properties and interconnections.
Represent problem	Convergent thinking - Formulating the problem
Experts spend considerable time to identify goal and describe how the problem can be solved in terms of concepts and principles in the given domain [9].	1. Identify goal 2. Remodel the system 3. Represent how the problem will be solved in the given domain.
	Phase 2. Design
Ideate	Divergent thinking - Generate multiple solutions
Attribute listing is a technique used to generate multiple ideas by first identifying all the attributes and its associated values in the subject. Then take one value from each attribute and combine to generate multiple ideas [11].	1. Identify the attributes and its associated values in the domain. 2. Draw attribute listing map. 3. Combine the values from each attribute to generate solutions.
Evaluation of solutions	Convergent thinking- Evaluate Solutions
Expert designers use decision matrix to evaluate and select the solution based on design criteria [10]. The most difficult skill is to identify the criteria and constraints to evaluate the solutions [2].	1. Pros and con analysis of solutions 2. Identify common parameters 3. Evaluate the solutions based on common parameters.
Select and Justify	Select and Justify
Monitor the solution- To justify one has to explain and reason how the selected solution satisfies the goal and constraints in the given problem [6].	1. Identify constraints in the problem 2. Use decision matrix to rank the solution based on constraints 3. Justify

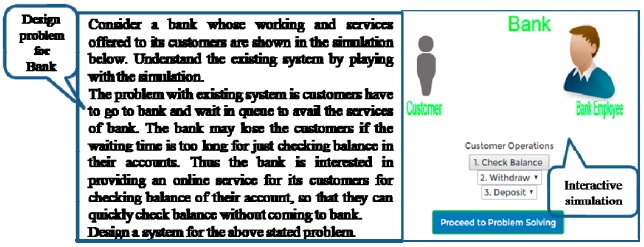

Fig. 2. The real life design problem with simulation posed to students

1.3. Problem solving phases with divergent and convergent thinking activities.

Students are systematically guided through two phases of problem solving- problem analysis and design. In each phase the students are guided to perform learning activities to trigger divergent to convergent thinking, The learning activities related to D & C thinking in each phase has scaffolds in form of prompts, explanation of new concepts illustrated with examples and simulations wherever necessary. These activities are also supported with domain specific hints to help students with low prior knowledge. The divergent and convergent thinking activities are explained below.

1.3.1 Divergent thinking activity- Understand the problem from multiple perspectives

After students read the problem and play with the simulation, the students are guided towards divergent thinking activity. The learning outcome of this activity is to understanding the problem from multiple perspectives of various stakeholders and entities, identify its properties and interconnections among entities. The prompt given was, *"Draw the model of a system to show its components, properties and interconnections*". The concepts like components, properties and interconnections are explained and illustrated with example as shown in figure 3. The domain specific hints are also provided to help applying skills while solving problem, for example one of the hint is- *"components are actors or entities involved in the given problem"*.

1.3.2. Convergent thinking activity- Formulate the problem

The learning outcome of this activity is to formulate the problem. the prompts given are i. *"Specify the goal to be achieved in the given problem"*, ii. "*Modify the model drawn in previous step to achieve the goal"*, iii. *"Formulate how the problem will be solved in the given domain"*. The domain specific hints were provided for each prompt, for example the hint given for prompt 3 was, "*Write the data and operations to be performed to achieve the goal*".

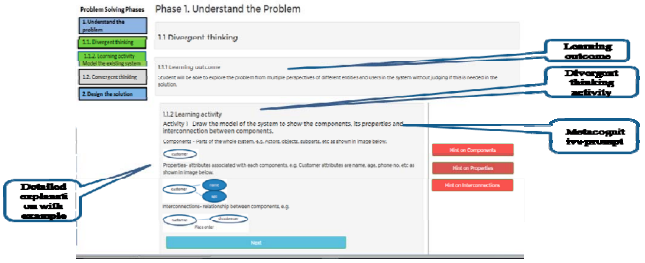

Fig. 3. Divergent thinking activity supported with metacognitive prompt and detailed explanation of activity.

1.3.3. Divergent thinking activity- Ideate

The learning outcome of this activity is to generate multiple solutions to the problem formulated in previous phase. First, the attribute listing technique is explained and illustrated with an animation. The animation showed the process of generating multiple designs of a table, by first listing the attributes and its values and combining them to generate multiple designs, as shown in figure 4.

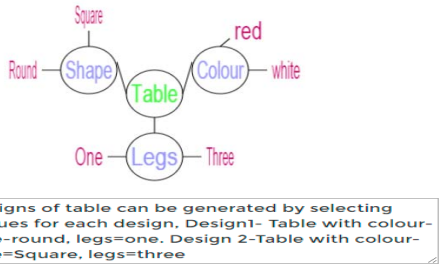

Fig. 4. Animation for generating multiple solutions using attributr listing

The table design simulation is shown to illustrate how attribute listing map is used to generate multiple designs using general example. Later, students are prompted to apply attribute listing map in data structure domain through the prompt- *i. "Draw the similar attribute listing map for domain-data structures"* and *ii. "Generate multiple solutions by combining the values of each attribute*".

1.3.4. Convergent thinking activity- Evaluate solutions

The learning outcome of this activity is to identify the criteria and evaluate the solutions. The prompt given was *"Write advantages and disadvantages of the solutions"*. The system generated a pros and cons analysis table preloaded with students' solutions to allow students to write advantages and disadvantages, as shown in figure 5.

Next prompt was-*"List the common criteria"* supported with example to illustrate the process of finding common parameters as shown in figure 5. Once the common criteria are identified and saved, the system generates an evaluation table to evaluate all solution based on common criteria.

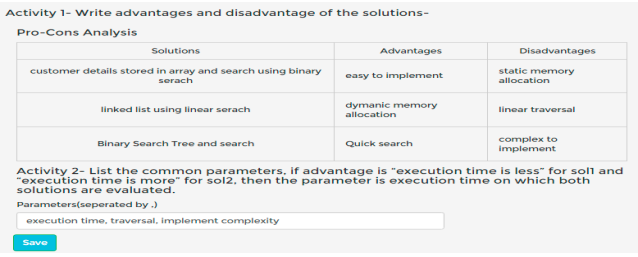

Fig. 5. Activity for pros and cons analysis table and identifying common criteria.

1.3.5. Convergent thinking activity- Select solution and justify.

The learning outcome of this activity is to identify constraints, select solution and justify. The prompt given to identify criteria is- *"Identify the constraints to be achieved in the problem"*. The explanation, example and hints given was- "*Constraints are the mandatory conditions to be achieved in the given problem. E.g. execution time should be low.* Then, a decision matrix is generated by the system with solutions listed in first column and constraints in first row and students are prompted to fill the table with yes/no based on whether the solution achieves the constraint and rank the solutions. At the end, students are prompted to justify.

2. Facilitating tools and artifacts for divergent and convergent thinking.

The learning environment is designed to facilitate students with tools and artifacts needed for D & C thinking. The divergent thinking activities are supported with drawing tool to draw the mental models of the system and attribute listing map to generate solution. The convergent thinking activities are supported with pros and cons analysis tables, evaluation table, decision tables, preloaded with solutions and criteria generated by the students to maintain the flow from one step to another. The text boxes are used in activities for writing goals, problem definition, solutions and justification. The response of the student in each step is stored in the database. These responses are fetched and loaded if student has already answered and wants to go back to the previous steps to refer to their answers.

IV. STUDY

The focus of our study was to investigate the research question - *"How effective is Fathom in learning divergent and convergent thinking skills?"*

The Fathom was developed and deployed on the web server with all the features except the drawing tool, thus the activity of drawing was done on paper.

1. Participants

Total 50 students from second year computer engineering participated in the study. The study was conducted at the end of the Data Structure course thus ensuring that students had enough domain knowledge to solve real life design problems in Data Structures.

2. Data Collection

Analysis of student D&C thinking activities-The answers provided by the students in Fathom were assessed based on how well students could perform the activity to demonstrate the sub-skills. The activities were given scores- high(3), medium(2) and low(1). Three points were given when the activity was performed as prompted.

For example, in divergent thinking activity-draw the mental model-three points were given if an accurate mental model was drawn showing all components (bank, customer, employee), data items(cust_id, name, balance, etc), and operations performed between entities(check_balance, withdraw, deposit, etc), two points was given when the activity was performed as prompted but had scope of improvement and one point was given when the activity was performed incorrectly.

Student perception survey- The student perception survey was taken to find how well the Fathom learning activities helped in achieving the desired learning outcomes. The survey had five likert scale- 5(strongly agree),4(agree), 3(neutral), 2(disagree), 1(strongly disagree) questions-

1. The divergent thinking activity of drawing the model of the existing system, helped in understanding the system better.

2. The convergent thinking activity of writing the goal and re-modeling the system, helped in formulating the problem.

3. The divergent thinking activity- ideate, helped in generating multiple solutions.

4. The convergent thinking activity of identifying parameters based on pros and cons analysis, helped in analyzing solutions.

5. The convergent thinking activity of identifying constraints and decision matrix helped in evaluating and justifying the selected solution.

Two open ended questions were asked to express their likes and dislikes about the system.

Student Interviews-After the training, four students were interviewed to get feedback on their learning of D&C skills and usefulness of activity.

V. RESULTS AND ANALYSIS

The RQ is answered based on the percentage of student's scores and student perception survey rating and student interviews. The percentage of student's scores at different levels-high, medium, low, in each activity and mean of perception survey rating are shown in table 2.

The scores given in table 2 show that the Fathom's learning activities and design features were effective in learning the D & C thinking sub-skills as percentage of scores in high and medium level are higher than percentage of scores in low level.

In divergent thinking activity-ideate, almost 90 % of the students generated 3 to 4 solutions, some of the solutions generated by students are- "1.*customer entity is represented using array and search operation is implemented using binary search, 2. customer entity is represented using array and search operation is implemented using linear search, 3. create a linked list with node account number, balance and traverse linked list"*. These activities were supported with prompts, detailed explanation of concepts, examples and simulations which helped students to perform better.

The activity- formulate problem and select solution, were supported with prompts only and lacked explanation, examples or simulations, thus only 50-60% of the students were not able to perform the activities. This is also supported with the student's response in open ended survey, that more simulations and examples are needed.

TABLE II. SCORES OF STUDENT PERFORMANCE AND STUDENT PERCEPTION SURVEY RATING

No of Students= 50	Activity	Divergent	Convergent		Divergent	Convergent					
						Evaluate solutions			Select & Justify		
	Sub-Skills	Draw mental model	Identify goal	Formulate	Ideate	Pros and cons analysis	Identify criteria	Evaluate solutions	Identify Constraint	Decision Matrix	Justify
Performance	Low	9%	38%	57%	21%	9%	15%	36%	38%	62%	53%
	Medium	74%	36%	21%	70%	61%	66%	23%	36%	21%	23%
	High	17%	26%	21%	9%	30%	19%	40%	26%	17%	23%
Student perception rating	[mean, SD]	4.11,0.52		4.06 ,0.6	4.09, 0.65			4.15, 0.59			4.09, 0.69

In activity- evaluate solution, 91% of students could do pros and cons analysis and 85 % of students were able to identify criteria-*"searching time, memory allocation, data size, operations allowed"* to evaluate solutions. The pros and cons analysis of data structures was taught to students while teaching the Data Structure course. Thus the activity was designed to connect to their prior knowledge in listing advantages and disadvantages of solutions and prompting them to think towards identifying common parameters.

The students perception rating (mean= 4.1) given in table 2, showed that students agreed that the Fathom's learning activities helped in achieving the desired D&C learning outcomes. Some of the student's responses in the open ended questions showed that activities helped in developing analysis and designing skills, building multiple solutions and gave knowledge on flow of how to solve problem. While some of the students found the whole process to be time consuming.

During interview, students perceived that the step by step guidance, prompts, examples and simulations helped to perform the activities. Some of the quotes of students on how activities helped are given below –

1. The overall idea of step by step guidance was good.
2. The activities helped us to figure out how many solutions are there, see what are the advantages and disadvantages that helped us to deduct which is the best solution for the problem.
3. Hints and examples helped us a lot when we were not able to understand what the problem was not clear. The improvements are needed in introductory and first phase- draw the model, identify goal and formulate, as students found it was difficult to understand what is needed compared to second phase. Some of quotes of the students suggesting improvement are

1. At the start, an introduction should be given to get clear idea of what to do, content was not clear for a new user to understand. Prompts were not enough.
2. The convergent thinking activity in design phase was nicely given and we moved faster, while struggling with first phase as we did not know what exactly is needed.

VI. DISCUSSION

For training a naïve learner in cognitive or metacognitive thinking skills, activities with only prompts are not effective if the concept or the skill is new to learner. The prompts should be supported with detailed explanation of new concept illustrated with examples and simulations. Only prompts are useful if prior knowledge is to be triggered, for example in our study students were competent in doing pros and cons analysis of data structures, thus only prompt was helpful in doing the activity. The system can be further improved by incorporating the feedback mechanism on adequate use of thinking skills.

VII. CONCLUSION

In this paper we discussed the design of the TEL environment to develop D & C thinking skills. The system is scaffolded with metacognitive prompts to systematically guide through D & C thinking activities. The study conducted to investigate the effectiveness of the learning activities showed positive results for activities supported with detailed explanation, examples, simulation.

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