Int. J. Engng Ed. Vol. 22, No. 3, pp. 551–559, 2006
Printed in Great Britain.
0949-149X/91 $3.00+0.00

Insisting on Truth at the Expense of Conceptualization: Can Engineering Portfolios Help?*

OZGUR ERIS
Center for Design Research, Stanford University, Stanford, CA 94305, USA.
E-mail: ozgur@cdr.stanford.edu

Teaching and promoting conceptual thinking in engineering education is challenging. Two recently introduced design thinking models are compared in order to explore the reasons behind this challenge. The comparison results in key distinctions between divergent and convergent thinking, and between concept and knowledge domains. The differentiating principle is shown to be a common principle of the two models, truth-value, or logical status, of the propositions that engineers make. Building on this insight, divergent thinking by inquiry is identified as a mechanism for promoting conceptual thinking, and a specific implementation of engineering portfolios is proposed as a pedagogical tool.

Keywords: conceptual thinking; divergent inquiry; engineering portfolios.

INTRODUCTION

THE DIVERGENT–CONVERGENT THINKING paradigm is often used to describe engineering design cognition. The generation of alternative designs is associated with the divergent component of the paradigm, whereas the reduction of alternative designs is associated with the convergent component. Depending on how the design process is viewed as a whole, this divergent–convergent movement can be treated as a cycle, and as the basis for iteration in design projects.

In engineering education, several pedagogical approaches are being applied in order to facilitate convergent thinking; these are mainly adaptations and derivatives of existing decision-making methods [1–4]. A smaller set of pedagogical approaches also exists for facilitating divergent thinking. Some of these approaches are direct applications of general creativity methods [5–8], and others are based on generative analytical methods used in a broad range of scientific fields [9].

Although methods for facilitating both types of thinking exist, application of methods that facilitate convergent thinking are preferred and emphasized to methods that facilitate divergent thinking. In this paper, the reasons for this bias are explained by comparing the principles of two theoretical frameworks that have been recently introduced: a question-based design thinking model, which describes design thinking as convergent and divergent inquiry [10], and a unified design theory, which defines design reasoning dynamics as a series of continuous transformations between the concept and knowledge domains [11].

Based on the outcome of this comparison, the promotion of divergent inquiry is identified as a meaningful approach for facilitating divergent thinking and overcoming the bias. Furthermore, engineering portfolios are proposed as environments in which students can engage in divergent as well as convergent inquiry, and are explored in the light of the two theoretical frameworks.

DIVERGENT–CONVERGENT INQUIRY BASED DESIGN THINKING MODEL

The main premise of the divergent–convergent inquiry based design thinking model (the DCIDT model) is that the activities that form the basis of engineering design projects are *question-driven*, and that engineering requires one to continuously question [10]. There is a substantial and growing knowledge base that supports this claim [12–16].

The DCIDT model, derived from data collected in the field and the laboratory, demonstrates that inquiry takes place in two fundamental modalities: divergent and convergent questioning. It identifies the incidence of a specific class of questions, deep reasoning questions[1], in engineering design team discourse as a manifestation of convergent thinking, and the incidence of another class of questions, generative design questions, as a

* Accepted 13 March 2006.

[1] Deep reasoning questions, termed by Graesser, were used to study learning interactions [17]. Their incidence was shown to correlate with student comprehension of scientific information [18].

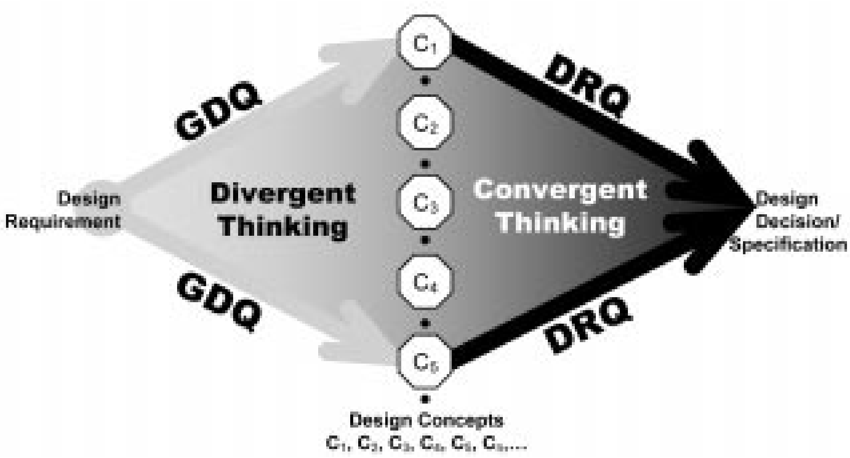

Fig. 1. The DCIDT model illustrates the transformation of requirements into concepts through Generative Design Questions (GDQs), and the transformation of those concepts into specifications through Deep Reasoning Questions (DRQs). (Source: Eris [10].)

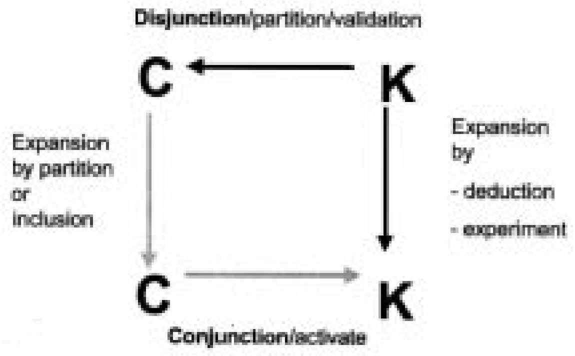

Fig. 2. The 'design square' consists of four types of transformations that take place within and between the concept and knowledge spaces. (Source: Hatchuel [11].)

manifestation of divergent thinking. The key distinction between the two classes of questions is the truth-value of the propositions that can be offered as answers. By definition, the answers to deep reasoning questions are expected to hold truth-value, whereas the answers to generative design questions are not.

According to the DCIDT model, effective inquiry in engineering design thinking entails both a divergent dimension in which generative design questions are asked to create, synthesize, and expand concepts, and a convergent dimension in which concepts are analyzed, evaluated, reduced, and validated by systematically asking deep reasoning questions (Fig. 1). The significance of this complimentary relationship is supported by the discovery of a correlation between only the combined incidence of deep reasoning questions and generative design questions and design performance of engineering teams during a simulated design exercise [10].

CONCEPT–KNOWLEDGE THEORY

Concept–Knowledge theory (C–K theory) is a unified design theory that defines design reasoning dynamics as a joint-expansion of the concept and knowledge spaces through a series of continuous transformations within and between the two spaces [11]. Therefore, C–K theory makes a significant distinction between the concept and knowledge domains: the knowledge space consists of propositions with logical status[2] for a designer, and the concept space consists of propositions without logical status in the knowledge space. In Hatchuel's words [11], 'concepts are candidates to be transformed into propositions of K but are not themselves elements of K.' In light of this definition of a concept, a key principle of C–K theory is that designing has no meaning in the absence of concepts since, if all is known, there is no need to create concepts that can be transformed into new knowledge.

More specifically, the transformations within and between the concept and knowledge spaces are accomplished by the application of four operators: concept → knowledge, knowledge → concept, concept → concept, and knowledge → knowledge (Fig. 2). These transformations form what Hatchuel calls the 'design square,' which 'gives the fundamental structure of the design process.' The last two operators are internal to the concept and knowledge spaces, and are not particularly relevant to this discussion. The first two operators cross the Concept–Knowledge domain boundary, and are significant in the sense that they reflect a change in the logical status of the propositions under consideration by the designer (from no logical status to true or false, and vice versa).

[2] As Hatchuel states, in standard logic, logical status can be either true or false.

[3] As defined by C–K theory.

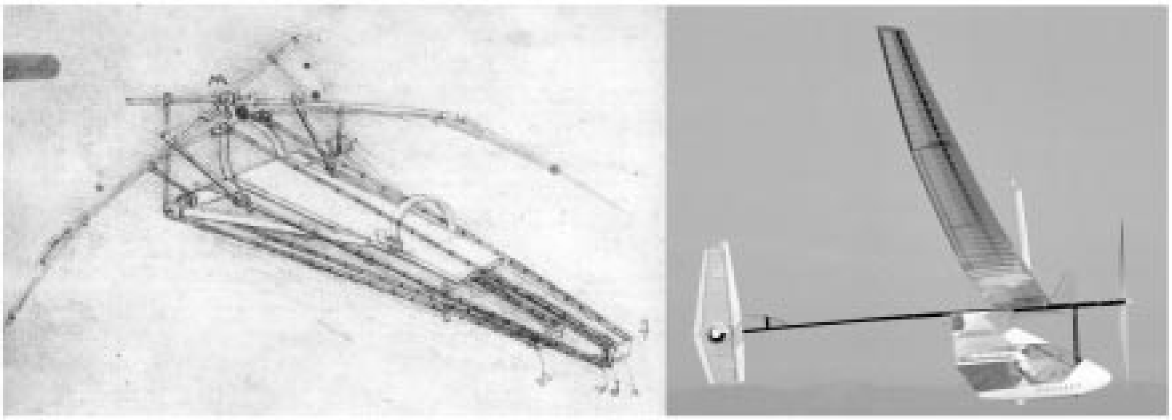

Fig. 3. On the left, Leonardo da Vinci's human flying machine concept [19]. On the right, the *Daedalus* human flying machine [20]. Da Vinci's proposition for a human powered flying machine did not hold truth-value at the time of conception, and therefore resides in the concept domain. *Daedalus* actually flew, and therefore resides in the knowledge domain.

PEDAGOGICAL IMPLICATIONS OF THE DCIDT MODEL AND C–K THEORY

Although the DCIDT model and C–K theory differ in scope, they share a key principle: design thinking takes place in distinct concept and knowledge domains. In C–K theory, the concept and knowledge spaces are explicitly defined. In DCIDT, the concept domain[3] coincides with the divergent inquiry space, where designers question in order to arrive at possibilities that can be generated from facts; and the knowledge domain[3] coincides with the convergent thinking space, where designers question in order to arrive at facts from possibilities. In both frameworks, the concept and knowledge spaces are differentiated according to the proposition under consideration having *truth-value,* or *logical status.*

At this point, it would be helpful to illustrate this differentiation with a specific example. Let us consider one of the most significant inventors of the renaissance era, Leonardo da Vinci. More specifically, let us consider a concept he explored in one his notebooks, the human flying machine (Fig. 3, left hand side), a human powered mechanical system that would fly. It can be argued that, while conceptualizing the machine, he was not particularly concerned with the truth-value, or logical status, of his proposition. If he was, and if he knew what we know today, he would have realized that the underlying aerodynamic properties of his concept were flawed (false). However, he did not know what we know today, and therefore, at that time, his exploration took place within the concept domain and was divergent in nature. On the other hand, centuries later, now that we understand the underlying aerodynamic properties of flight, a team of NASA and MIT engineers were able to validate da Vinci's concept and achieve human powered flight in the form of the *Daedalus*. Somewhere in between da Vinci's thinking and the flight of the Daedalus, da Vinci's original concept was expanded on by modifying the power delivery mechanism—most likely an outcome of divergent inquiry. Today, the *Daedalus* itself resides in the knowledge domain; we know that it flies! And, it is reasonable to assume that to make it fly, its designers acted on da Vinci's concept and engaged in a convergent inquiry process.

A discussion on the pedagogical implications of the truth-value differentiation principle of the DCIDT model was initiated in a recent article by Dym *et al.* [16]. It was argued that the current engineering curricula are primarily concerned with the acquisition of knowledge associated with mathematics and sciences, and the application of that knowledge in solving engineering problems. This was identified as an epistemological approach[4], in which known, validated principles are leveraged in applying an inquiry process to analyze and describe a constrained situation, the problem, in order to reach true answers or solutions.

Based on the discussion in the previous section, epistemological inquiry can be interpreted to be associated with the knowledge → knowledge and concept → knowledge operators of C–K theory, since it does not result in the creation of concepts. And, according to DCIDT, epistemological inquiry is convergent in nature since it yields answers with truth-value.

Dym *et al.* also argued that while it is critical for engineering students to master the epistemological inquiry process that is being successfully taught in most engineering curricula, real-world situations also require them to consider answers that do not hold truth-value, which means that engineering students need to learn how to operate in the concept domain and master divergent inquiry as well convergent inquiry. In other words, engineering education might be insisting on truth at the expense of conceptual thinking. Thus, the leading question for the rest of the discussion in this paper becomes: How can we promote divergent inquiry

[4] The principles of the epistemological inquiry approach can be traced back to Aristotle [21].

in engineering education as a process complimentary to the epistemological inquiry process?

Prior to answering this question, it might be useful to consider how convergent inquiry is currently being promoted, and if divergent inquiry can be promoted by using similar methods. In engineering education, which has traditionally fostered a high level of competition among students, one of the main incentives for students to adopt a specific method or behavior is to obtain a high grade; students are mainly concerned with how they will be graded, and respond accordingly [22]. Judging how well a student has followed the epistemological approach to reach a truth answer is relatively straightforward and objective; the truthfulness of an answer can be verified (in relation to constraints, assumptions, and scientific principles), and the application of the process can be evaluated (identification of relevant principles, and presence or absence of analytical steps).

On the other hand, let us consider how divergent inquiry is currently being promoted. Although insightful approaches for promoting divergent thinking in the context of creativity exist [5–9], they have not been incorporated into engineering curricula in a meaningful way. When they are used in a course, they are usually presented as 'experimental' activities that can broaden minds and facilitate team building. It is highly unlikely that an engineering student has ever been asked or expected to apply de Bono's thinking hats method to generate new concepts, or Adams's thinking outside of the box approach to challenge and negotiate constraints in tackling an engineering science course final examination. This scenario is especially relevant if we consider that written examinations, and problem sets resembling written examination questions, are the core grading instruments in most engineering classes.

Even in project-based engineering design courses, the main grading criteria remain predominantly in the knowledge domain: Did the designers perform the epistemological inquiry process to determine if the concept would 'work'? Did the design function as intended? Did the design win the contest? Functionality of the outcome of the project tends to be overemphasized. Limited partial credit might be given for demonstrating divergence as a part of the 'design process,' but that is not enough to motivate students to learn and adopt such thinking. And, in many cases, project-based approaches are used with the intention of conveying discipline specific content, which results in the project having, as Faste put it [23], 'a hidden correct answer or preferred set of answers.'

In the case of examination questions, it would not be acceptable for students to respond by providing several possible concepts that do not have truth-value. Instead, students would be expected to engage in convergent inquiry, build up to and formulate deep reasoning questions, and work their way to 'the answer.' They would be judged on their ability to converge even if their answers are incorrect; partial credit would be given for demonstrating a deterministic thought process. Similar to examination questions, problem sets also yield right or wrong answers [22].

Perhaps, the real issue is not whether examination questions that would require students to engage in divergent inquiry can be formulated, but how an instructor would go about grading

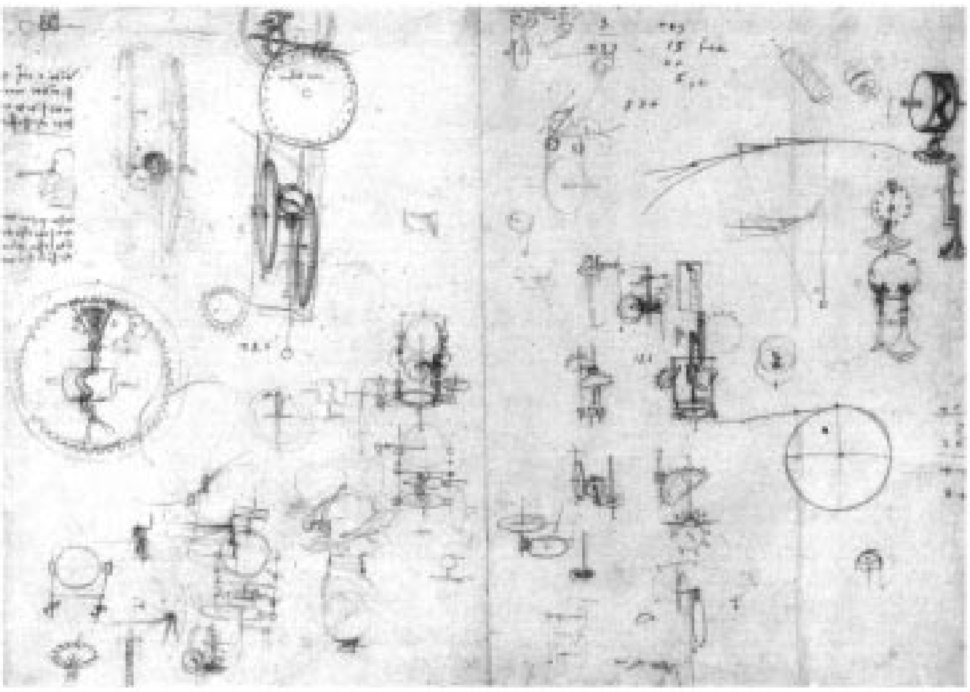

Fig 4. Leonardo da Vinci's exploration of mechanism concepts for a humanoid robot [24].

responses to such questions [16]: How can instructors objectively grade the conceptualization performance of students, since concepts are neither true nor false? And, returning to our guiding research question, how can we promote divergent inquiry in engineering education as a complimentary process to the epistemological inquiry process? In the next section, one of the many possible answers to these two questions will be discussed in detail.

CAN ENGINEERING PORTFOLIOS HELP?

It is common practice for professional engineers to use notebooks in order to document and build on their work. In engineering design courses, students are increasingly encouraged, and in some cases, required, to keep design notebooks. Traditionally, a design notebook has been a physical artifact, a notebook resembling a journal with blank pages, which a designer personally owns and fills out while engaged in his/her work. Leonardo da Vinci's notebooks are striking classical examples. Two pages of one of his notebooks, where he has explored mechanism concepts for a humanoid robot are shown in Fig. 4.

An inspection of the two pages reveals that da Vinci's thinking is highly divergent and conceptual. While he has applied knowledge of gears and mechanisms in generating several variants of concepts, his thinking is predominantly divergent in nature and resides in the concept domain. There are a broad range of references, such as the human body, geometrical shapes, gears, pulleys, and numbers. There is no clear linear path, answer, or solution. Although it is impossible to know what types of questions da Vinci was asking of himself verbally, it can be argued that the diversity of his considerations and expressions constitutes evidence of his divergent inquiry visually. Then, it appears that design notebooks have a certain affordance for supporting the divergent inquiry process. Let us explore this proposition further.

In the light of recent developments in information technology, the definition of a design notebook is being broadly interpreted. Software tools resembling and extending the functionality of physical notebooks are becoming more sophisticated and widespread. Individual portable computers, due to their mobility and computing power, are acting as catalysts in the adoption of electronic notebook software [25]. Also, the networking capability introduced by the Internet is giving designers ubiquitous access to a variety of information sources, and allowing them to share parts of their notebooks with others [25–27], blurring the boundary between individuals and groups.

More specifically, engineering design notebooks, in either physical or electronic form, can help designers to: externalize and organize their thought and work processes [26, 27]; document their ideas so that they are not forgotten [28]; capture design rationale so that it can be reused in the future to understand the basis for past decisions and fuel new explorations [29–31]; reflect on their work and learning [27,31]; and communicate and negotiate their ideas with their peers [28–31].

There are similar practices and developments in fields other than engineering. The use of portfolios, which is characteristic of fine arts education, has been gaining increasing acceptance in humanities education as a learning and assessment tool [32, 33]. Portfolios are seen as powerful alternatives to examinations, since they allow students as well as instructors to gain a much more comprehensive, and even holistic, understanding of students' learning paths and outcomes.

In this paper, the notion of engineering portfolios is proposed as one potential answer to the questions posed at the end of the previous section for the following reasons:

1. Portfolios are effective in externalizing students' learning *processes*—not just their learning outcomes—and therefore, provide opportunities for making process-related interventions. Since this paper is concerned with finding ways of promoting the divergent inquiry process as a part of engineering education, a process-based learning paradigm would be most appropriate for making interventions. For instance, students can be asked to formulate, explore, and document generative design questions related to the subject they are studying in their engineering portfolios. A similar method, where students were asked to respond to assignments by formulating questions as opposed to answers was experimented with in Stanford Mechanical Engineering 206: Vehicle dynamics [34]. Over 90% of the students reported that the method enhanced their understanding of the subject. Sensitizing students to the principles of DCIDT and asking them to formulate specific type questions in specific situations would extend this idea.
2. As Leonardo da Vinci's design notebooks so vividly illustrate, portfolios, by their very nature, are open-ended and support the type of intellectual exploration that promotes divergent inquiry and yields multiple answers. The contents of an engineering portfolio that are related to conceptual exploration do not need to hold truth-value. Also, they can draw upon a variety of sources, experiences, actors, expressions, etc. The mere possibility of being able to integrate and work with information from such a diverse set of dimensions constitutes divergent inquiry in itself! Although one could argue this could lead to fragmentation in the learning experience, such issues can be addressed with appropriate instructional support. For example, Chen *et al.* [26] are experimenting with applying coaching support to portfolio development in engineering courses.
3. Since portfolios are capable of accommodating different kinds of learning content, they should also be able to support the type of learning

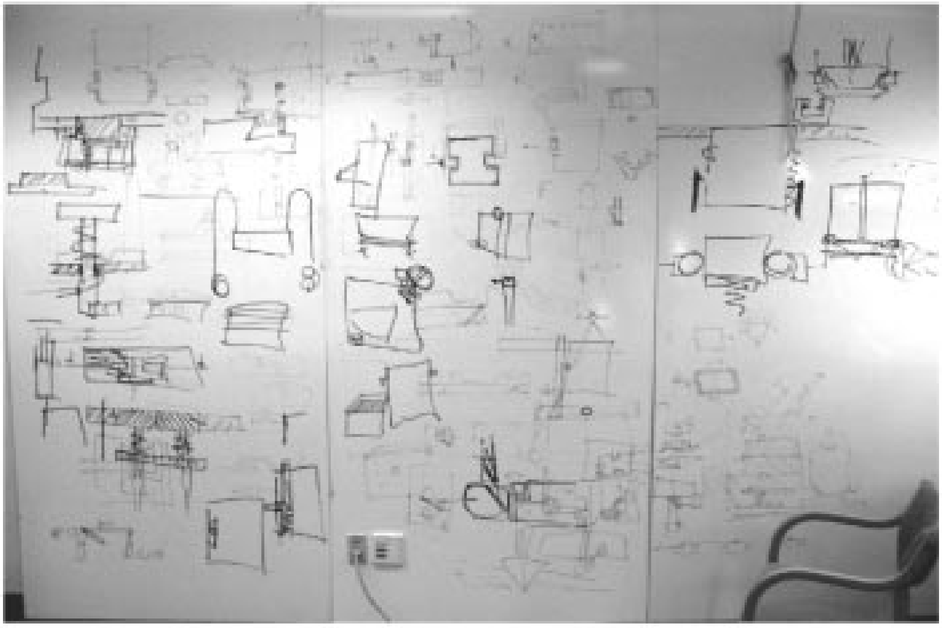

Fig 5. Outcome of an engineering team meeting: Numerous concepts sketched on a large (12 × 7 ft.) whiteboard at the Stanford Center for Design Research [35].

activity that is associated with epistemological inquiry. After all, the goal of this paper is not to find ways of promoting divergent inquiry in engineering education for its own sake; it is to find ways of promoting divergent inquiry so that its products, concepts, can be acted on by the application of the epistemological inquiry process that is already being successfully conveyed in engineering education. That is why 'engineering portfolios' are being proposed rather than 'design portfolios' as an answer to the guiding research question.

For instance, in a mechatronics course, students can use their engineering portfolios as an environment in which they conceptualize novel electromechanical systems to satisfy user needs, and in conjunction, *within the same environment*, work on problem sets on circuits and mechanisms to learn the relevant fundamental scientific principles. It is very plausible that after engaging in these different inquiry processes for a period of time within the same environment, students would naturally be able to see connections and bridge them, or at least, would be more open to responding to pedagogical interventions that are aimed to relate them.

4. Although the use of engineering portfolios would not necessarily offer an objective approach to grading conceptualization performance of students—concepts are neither true nor false regardless of the environment they are expressed in—as mentioned in the first point, it would make their divergent inquiry process more explicit and transparent. This would constitute a base layer upon which evaluation criteria can be superimposed; one cannot evaluate what one cannot observe.

If these four points are considered in the context of the initial discussion on the DCIDT model and C–K theory, an attribute of engineering portfolios is revealed: engineering portfolios should consist of conceptual partitions in which divergent inquiry is exercised, and knowledge-based partitions in which epistemological inquiry is exercised. Although these partitions are distinct for the most part, their development is contingent on each other; the contents of one type of partition feeds into the other.

Let us walk through a realistic usage scenario for engineering portfolios—as they are defined in this paper—to illustrate what has been proposed so far, and to demonstrate that they are indeed tangible and relevant to promoting an effective inquiry process in engineering education. Let us consider an experience the author had when he came to work one day and was confronted with a rich set of chaotic sketches that filled up a large whiteboard in his workplace (Fig. 5). It also happened that the author had been studying Leonardo da Vinci's notebooks the day before as a part of his research for this paper. The reader should be able to imagine how delighted the author was as the resemblance between the sketches in Leonardo da Vinci's notebook and the sketches on the whiteboard is striking (compare Figs 4 and 5); not in content but in the kind of conceptual exploration and visual divergence that has been displayed.

The author was able to determine that the sketches were generated during the meeting of a student team in an engineering course. Their goal was to develop a 'wireless switch' to be used in an automotive application. Based on the sketches, it can be assumed that the students were in a generative mode, and were not particularly interested in the truth-value of the concepts while they were creating them. A brief conversation with one of the students confirmed this assumption. The author then took a picture of the board with a digital camera (after obtaining the student's consent), and pasted the image into this paper. The documentation process took less than 45 seconds. If the student was using an engineering portfolio, he would have gone through the same documentation procedure, and pasted the digital image into his engineering portfolio.

If we are to consider the proceeding events hypothetically, we can imagine that the student would generate more concepts for the wireless switch. He could generate them within his portfolio, or import them into his portfolio from wherever they were generated. In the meanwhile, it is reasonable to assume the student would also be considering the scientific principles behind some the concepts he has generated by engaging in a convergent inquiry process to identify the most effective wireless transmission frequencies, power source, and materials. The student could carry out those analyses in his portfolio, or import them into his portfolio from elsewhere.

A pedagogical intervention would be to require the student explicitly to formulate sets of generative design questions and deep reasoning questions in his portfolio, and to use those questions to structure his divergent–convergent inquiry processes and learning activity.

HOW CAN ENGINEERING PORTFOLIOS BE GRADED?

Let us now consider how an engineering portfolio can be graded. From the distinction made in the previous section, it follows that conceptual and knowledge-based partitions of an engineering portfolio should be graded differently since they are outcomes of distinct thought processes. Grading knowledge-based partitions should be relatively straightforward and objective since existing methods for evaluating the student's ability to perform the epistemological inquiry process can be used.

However, depending on the nature of the problem/project that is being studied by the student, it may be necessary to engage multiple instructors in grading since a single instructor might not have the knowledge base to assess the validity of the convergent inquiry processes and the truth-value of the outcomes for a broad range of subjects. For instance, in the 'wireless switch' development scenario, the student might be applying scientific principles from different fields such as signal processing, material science, and strength of materials. The engagement of multiple instructors in grading would be resource intensive, and inevitably raise a feasibility issue. On the other hand, if the nature of the problem/project under study remains within the bounds of a specific field, this would not be an issue.[5]

Grading the conceptual partitions would be more challenging. Assigning a grade to the quality of an outcome that has no truth-value is problematic, and is mainly an aesthetic consideration. However, the divergent process used to generate the outcomes can be evaluated by using existing criteria: How many concepts were generated? How diverse are the concepts? How well are the concepts communicated? How comprehensively are the concepts explored? These types of criteria are currently being used to evaluate student design notebooks by Neeley [36] in an introductory engineering course, Stanford University's Mechanical Engineering 101: Visual Thinking.

The following can constitute criteria derived from the DCIDT model (assuming students were asked to formulate and document their guiding questions): How many generative design questions were asked? How many different types of generative design questions were asked? What percentage of the generative design questions that were asked was addressed? How divergent was the inquiry process intellectually? Did the divergent inquiry process build on itself?

An issue remains mainly unresolved: Although engineering portfolios can establish a useful framework for promoting and documenting divergent inquiry, and outline criteria for grading the conceptualization performance of students, they do not specify as to how an instructor can objectively go from a set of observations that fall under a criteria to a specific grade.

One solution would be to consider using a subjective approach for evaluating conceptual performance of engineering students—similar to the one used in arts education. For instance, in a creative writing or photography course, it is highly unlikely for an instructor to break down the grade given to an assignment into several categories and objectively (and quantitatively) evaluate the work according to each category. It is much more likely for the student to receive a single grade, and be provided with qualitative (and somewhat subjective) comments regarding the grade. In other cases, the student might receive qualitative comments on each assignment, and not receive a grade until the end of the course. However, it should be noted that there is no consensus among arts educators as to how grades should be assigned either [37]. Many of them strongly reject the notion of grading altogether.

In engineering education, subjective grading approaches are almost unacceptable, and for a

[5] This is not to say the author is advocating limiting the use of engineering portfolios to a specific field. The reader is encouraged to consider the implications according to his or her pedagogical goals.

good reason! A plane either lifts off at the end of the runway, or it crashes. A bridge either withstands the weight of rush-hour traffic, or it collapses. However, as argued for throughout this paper, that is not the complete 'engineering picture.' Those are not the only criteria for which engineering students should be held accountable. They should also be held accountable for generating new concepts for flight, and different ways of crossing a river, which are difficult to grade objectively, and require subjective judgment. There is emerging evidence suggesting that subjective grading approaches in engineering education, when used in the appropriate context, are not as problematic as expected [38], and that students 'come to realize that subjectivity represents the work place.'

As engineering educators, we might need to ask ourselves: Are we holding students accountable for criteria that are predominantly objective because that is the only way we know how to assess? How comfortable are we with subjectivity when we need to be subjective, when there is no truth-value to be found?

CONCLUSION

In this paper, two recently introduced frameworks, the divergent–convergent inquiry based design thinking model and the concept–knowledge theory, were used as frameworks for exploring why methods that promote conceptual thinking have not been fully integrated in engineering curricula. A common principle of the two frameworks, truth-value, or logical status, of the propositions that engineers consider when engaged in engineering activities was instrumental in guiding and grounding the discussion. It was argued that the epistemological approach, which is the basis of engineering education today, requires students to be overly concerned with truth, and that this comes at the expense of conceptual thinking since concepts, by definition, do not have logical status.

The notion of engineering portfolios, derived from design notebooks and considered in the context of engineering activity as a whole, was proposed as an environment in which students can effectively engage in divergent inquiry and conceptual thinking. Four reasons as to why engineering portfolios would promote divergent inquiry as a complimentary process to the epistemological inquiry process were articulated in detail, and some example usage scenarios were provided. Based on those reasons, it was argued that engineering portfolios should consist of conceptual partitions in which divergent inquiry is exercised, and knowledge-based partitions in which epistemological inquiry is exercised.

Evaluation criteria for engineering portfolios were also considered. It was argued that the conceptual performance displayed by students in their portfolios would need to be graded in order to ensure balanced emphasis between conceptual and knowledge-based partitions. Grading conceptual performance was recognized to be problematic since concepts are neither true nor false. Criteria for evaluating divergent inquiry and conceptual thinking processes as opposed to concepts, which are outcomes of those processes, were considered. It was argued that when grading according to such criteria, subjectivity might be necessary.

The author is planning to experiment with and test the proposed definition and usage of engineering portfolios in the near future in engineering classes. Validation of the engineering portfolio concept would have significant implications for integrating conceptual thinking in engineering curricula.

Acknowledgement—This research is funded by the National Science Foundation under Grant No. 0230450.

REFERENCES

1. G. A. Hazelrigg, An axiomatic framework for engineering design, *Journal of Mechanical Design*, **121**, pp. 342–347, 1999.
2. S. Pugh, Concept selection: A method that works, in *Creating Innovative Products Using Total Design*, D. Clausing and R. Andrade (eds.), Addison-Wesley, Reading, MA, (1996).
3. W. H. Wood, Decision-based design: A vehicle for curriculum integration, *International Journal of Engineering Education*, **20**(3), pp. 433–439, 2004.
4. G. E. Dieter, *Engineering Design: A Materials and Process Approach*, McGraw-Hill, New York, (1983).
5. E. De Bono, *Serious Creativity: Using the Power of Lateral Thinking to Create New Ideas*, Harper Business, New York, (1992).
6. J. Adams, *Conceptual Blockbusting: a Guide to Better Ideas*, Fourth edition, Perseus Publications, Cambridge, MA, (2001).
7. W. J. Gordon, *Synectics: The Development of Creative Capacity*, Harper and Row, New York, (1961).
8. A. Osborne, *Applied Imagination; Principles and Procedures of Creative Thinking,* Scribner, New York, 1957.
9. K. W. Norris, The Morphological Approach to Engineering Design, in *Conference on Design Methods*, J.C. Jones and D. Thornley (eds.), Pergamon Press, Oxford, (1963).
10. O. Eris, *Effective Inquiry for Innovative Engineering Design*, Boston, Massachusetts, Kluwer Academic Publishers, (2004).
11. A. Hatchuel and B. Weil, A new approach of innovative design: An introduction to C–K theory, *Proceedings of the International Conference on Engineering Design*, Stockholm, Sweden, (2003).

12. V. Baya, Information handling behavior of engineers in conceptual design: Three experiments, Doctoral Dissertation, Stanford, California: Stanford University, 1996.
13. A. Mabogunje, Measuring conceptual design performance in mechanical engineering: A question based approach, Doctoral Dissertation, Stanford, Stanford University, California, 1997.
14. J. R. Marsh, The capture and structure of design experience, Ph.D. dissertation, Cambridge University, Cambridge, UK, 1997.
15. H. Gedenryd, How designers work, Ph.D. dissertation, Lund University, Lund, Sweden, 1998.
16. C. Dym, A. Agogino, O. Eris, D. Frey and L. Leifer, Engineering design thinking, teaching, and learning, *Journal of Engineering Education*, (January), 2005, pp. 103–120.
17. A. Graesser, K. Lang and D. Horgan, A taxonomy for question generation, *Questioning Exchange*, **2** (1), pp. 3–15, 1988.
18. A. Graesser and N. Person, Question asking during tutoring, *American Educational Research Journal*, **31**(1), 1994, pp. 104–137.
19. Leonardo da Vinci, sketches of a human powered flying machine, Ms. B. (IFP), fol. 74v.
20. http://www.dfrc.nasa.gov/gallery/photo/Daedalus
21. Aristotle, *Posterior Analytics*, J. Barnes (translator), 2nd edn, New York, Oxford University Press, (1994).
22. R. Faste and B. Roth, The design of projects and contests—the rules of the game, *Journal of Robotics and Mechatronics*, **10**(1), 1997.
23. R. Faste, B. Roth and D. J. Wilde, Integrating creativity into the mechanical engineering curriculum, Proceedings, *Innovations in Engineering Design Education*, ASME, 1993, pp. 93–98.
24. Leonardo da Vinci, studies of elements of a humanoid robot, Codex Atlanticus (BAM), fol. 1077r.
25. D. J. Nicol and I. A. MacLeod, Using a shared workspace and wireless laptops to improve collaborative project learning in an engineering design class, *Computers and Education*, **44**(4), 2004, pp. 459–475.
26. H. Chen, D. Cannon, J. Gabrio, L. Leifer, G. Toye and T. Bailey, Using Wikis and Weblogs to support reflecting learning in an introductory engineering design course, to appear in the *Proceedings of the American Society for Engineering Education*, Portland, Oregon, 2005.
27. M. Campbell and K. Schmidt, Polaris: An undergraduate online portfolio system that encourages personal reflection and career planning, *International Journal of Engineering Education*, **21**(5), 2005.
28. G. Toye, M. R. Cutkosky, L. J. Leifer and J. M. Tenanbaum, A methodology and environment for collaborative product development, *International Journal of Intelligent and Cooperative Information Systems*, **3**(2), 1994, pp. 129–153.
29. M. Yang, Retrieval of informal information from design: A thesaurus based approach. Ph.D. dissertation, Stanford University, California, USA, 2000.
30. J. Hong, G. Toye and L. J. Leifer, Personal electronic notebook with sharing, *Proceedings of the Fourth Workshop on Enabling Technologies: Infrastructure for Collaborative Enterprises*, Berkeley Springs, WV, (1995).
31. F. Lakin, J. Wambaugh, L. Leifer, D. Cannon and C. Sivard, The electronic design notebook: Performing medium and processing medium, *Visual Computer: International Journal of Computer Graphics*, **5**(4), 1989, pp. 214–226,.
32. P. Belanoff and M. Dickson (eds), *Portfolios: Process and Product*, Boynton/Cook Publishers, Inc., Portsmouth, NH, (1991).
33. C. Porter and J. Cleland, *The Portfolio as a Learning Strategy*, Boynton/Cook Publishers, Inc, Portsmouth, NH, (1995).
34. A. Mabogunje, J.C. Gerdes, J. Nash, C. Dornbush, E. W. Johnson, Critical skills for the 21st century: Asking better questions (video recording), A Stanford Learning Lab Experiment, Stanford University, California, 1999.
35. M. Jung, whiteboard sketches of a wireless switch (digital image), Stanford Center for Design Research, 2005.
36. L. Neeley (Co-Instructor), Mechanical Engineering 101: Visual thinking, Sheppard, S., (Instructor) Stanford University, Spring Quarter, 2005.
37. M. Ross (ed.), *Assessment in Art Education: A Necessary Discipline or a Loss of Happiness*, Pergamon Press, New York, (1986).
38. E. Pappas and R. Hendricks, Holistic grading in science and engineering, *Journal of Engineering Education*, **89**(4), 2000, pp. 403–408.

Ozgur Eris is the Associate Research Director of the Center for Design Research at Stanford University. His research interests include engineering design theory, design cognition, and design informatics. He received a BS from the University of Washington, and an MS and a Ph.D. in Mechanical Engineering from Stanford University. He has published on the role of inquiry in design, design knowledge and capture, and interdisciplinary aspects of creativity. He is the author of *Effective Inquiry for Engineering Design* (2004).