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Comprehensive Design Engineering: Designers Taking Responsibility*

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There is a growing awareness that we have been overproducing rigorously disciplined, game-playing specialists who, through hard work and suppressed imagination, earn their academic union cards, only to have their specialized field become obsolete or by-passed by evolutionary events of altered techniques and exploratory strategies. As R. Buckminster Fuller said: 'We need the philosopher-scientist-artist—the comprehensivist, not merely more deluxe-quality-technician-mechanics.' Comprehensive Design Engineering (CDE) is a roadmap for a new curriculum intended to be the next step in Stanford's Product Design Program. Building on Fuller's notion of a 'comprehensivist', this forward-looking curriculum brings together business, human issues, and technology in a comprehensive manner to support the creation of tomorrow's innovations. This integrated academic program consists of Bachelor's, Master's, and Ph.D. degrees in the Comprehensive Design Program. Bringing the students through models and experiments of the what, how, and why innovations occur in emerging technologies, the program prepares students at all degree levels to bring value to the organizations they belong to. This paper describes the frameworks used in CDE to enable consistent innovation.

INNOVATION CONTEXT

GEOFFREY MOORE'S Chasm Model has become the dominant framework in which to discuss the development of the markets for high-technology products and services. This model assumes that a product exists at the beginning of the life-cycle. The work of the designer begins well before Moore's model, as shown in Fig. 1. The engineer is part of a team that transitions technology from the R&D centers into product architectures. There is a similar life-cycle for this transition of technology into an innovative product. There is also an analogous gap to the Chasm, referred to here as the Innovation Fence. The British economist, Shanks, states that 'There is a wide gap in every country between the knowledge of new products, process, and techniques and the successful application of that knowledge in industry . . . The gap is not just a matter of ignorance, however. The company, and the country, that can best . . . bridge the gap between knowledge and application will succeed in the economic struggle; those that fail will go under . . . But neither at company nor at national level can the opportunities presented by modern technology be grasped without a clear and conscious *strategy*, and without accepting all the implications of a change' [1]. The Innovation Fence is the hurdle technology must jump before it is ready to be integrated into a product or service. This Fence cannot be crossed without the assistance of the 'comprehensive designer'. Fig. 1 illustrates both cycles and the critical transition points for an innovation to make it into the greater market.

Enabling designers to cross the Innovation Fence is the goal of the Comprehensive Design Engineering program. Current design and engineering curriculums do not equip designers with the tools and skills necessary to take responsibility for transitioning technology and products across the Innovation Fence and into the hands of needy customers. Fig. 2 illustrates this curricular gap that exists in current education programs to train and assist graduates in successfully breaking through the Innovation Fence [5].

An effort to fill this gap is the development of a new educational framework, Comprehensive Design Engineering (CDE). Current academic programs live at a different part of the spectrum than Fuller's ideal. There is a growing demand for the skills Fuller describes here. Stanford's Product Design program seeks to rise to Fuller's challenge. The CDE framework illustrated in Fig. 3 uses design to connect across disciplines to develop innovation skills. This forward-looking curriculum brings together business, human issues, and technology in a comprehensive manner to support the creation of tomorrow's innovations. This radically integrated academic program consists of Bachelor's, Master's, and Ph.D. degrees in the Comprehensive Design program. Bringing the students through models and experiments of the what, how, and why innovations occur in emerging technologies, the program prepares students at all degree levels to bring value to the organizations they belong to. Fig. 3 frames the three disciplines of CDE and identifies existing domains within the framework.

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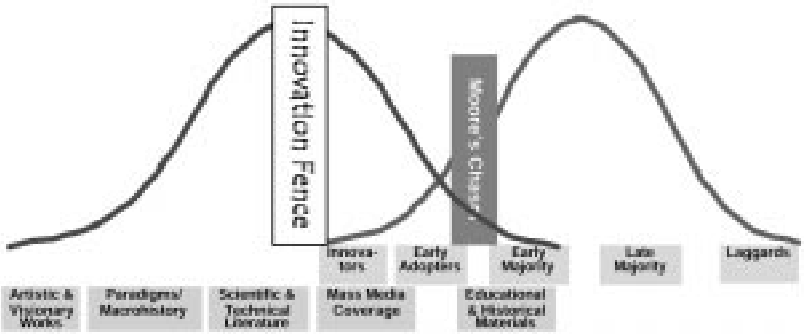

Fig. 1. Everett Rogers' innovation diffusion curve [2] with Geoffrey Moore's Chasm [3] and the bibliographic cycle of technological innovations [4] with the Innovation Fence included. The Innovation Fence is the hurdle a technology must cross before it finds its way into a product. Designers work to help technology over this fence and into products.

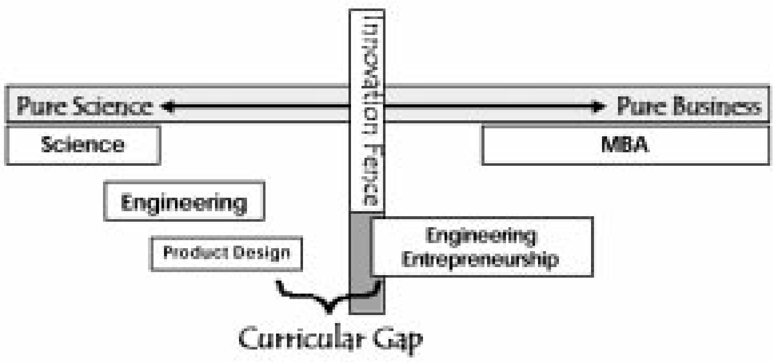

Fig. 2. Diagram of the Innovation Fence showing how various academic programs cover the transition of technology into the marketplace. Crossing the Innovation Fence is a critical skill for students to attain. Currently, no academic programs assist students in developing this skill or even awareness of the transition across the fence.

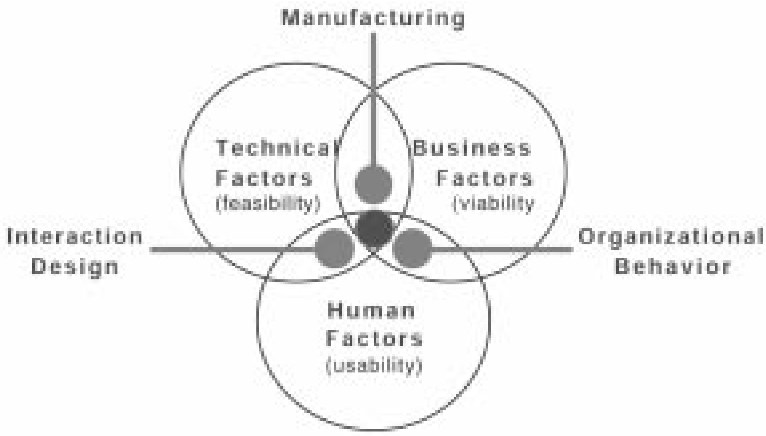

Fig. 3. Comprehensive Design Engineering is an extension of IDEO's Innovation Engine, documented by Weiss [6], based on Asimow's [7] definition of effective design, which 'requires a synthesis of technical, human, and economic factors.' This extension brings together Technology Issues, Business Issues, and Human Issues within a particular context to create a comprehensive program that enables consistent brilliant innovation.

Stanford's Product Design Program established itself professionally and academically through the thoughtful integration of art and engineering. CDE represents the next logical step in learning and practice. Initially encouraging specialization within one of the Comprehensive Design Engineering sub-domains, the program also requires the honing of comprehensive skills in technology, business, and human issues. The technology piece consists of multidisciplinary engineering experiences that blend theory and experience, such as mechatronics or biomechanical systems. The business piece encompasses predominately entrepreneurship education. Leveraging the world-class programs supported by the Stanford Technology Venture Program (stvp.stanford.edu), CDE enriches student capabilities through contextual coursework that explores and experiences innovation

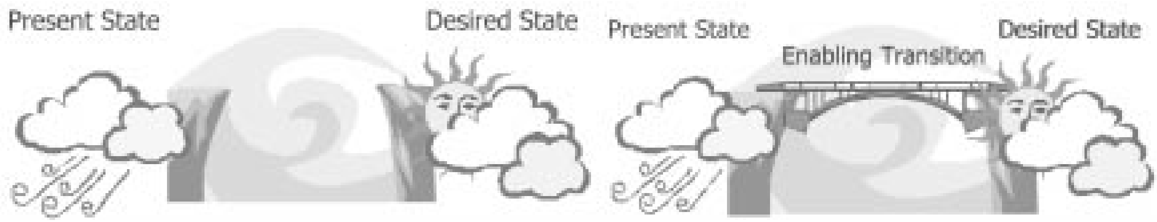

Fig. 4. Illustration of 'need', demonstrating the perceived gap between the present state and desired state of an entity. This perceived gap is valid for a particular context that must be explicitly stated. 'Solutions' are creations that bridge the gap between the present state and the desired state. Solutions can be Products, Process, Services, or some combination of all three, depending on the nature of the gap to be bridged.

and entrepreneurship. Human issues contain critical elements that are often neglected in other programs: human factors, human computer interface design, aesthetics, and organizational design.

INTELLECTUAL FRAMEWORKS OF COMPREHENSIVE DESIGN ENGINEERING

Comprehensive Design Engineering makes use of several developing frameworks to support the transformation of CDE stakeholders into comprehensive innovators. These frameworks provide CDE participants with a common language and understanding of innovative practice. The 'innovation chain' provides insights as to the evolution of innovations. The 'need–solution' framework assists designers in understanding the process activities of consistent innovation. The 'innovation impact map' provides a framework to assess candidate innovations for their impact in the technical, human, and business domains.

Need–solution framework

Esther Dyson encourages 'creative solutions to real problems' while discouraging innovation for innovation's sake [8]. Mary Lou Maher uses genetic algorithms to create innovative architecture designs by co-evolving design requirements and design solutions [9]. Adams *et al.* found empirical evidence of this co-evolving iteration between problems and solutions [10]. These three

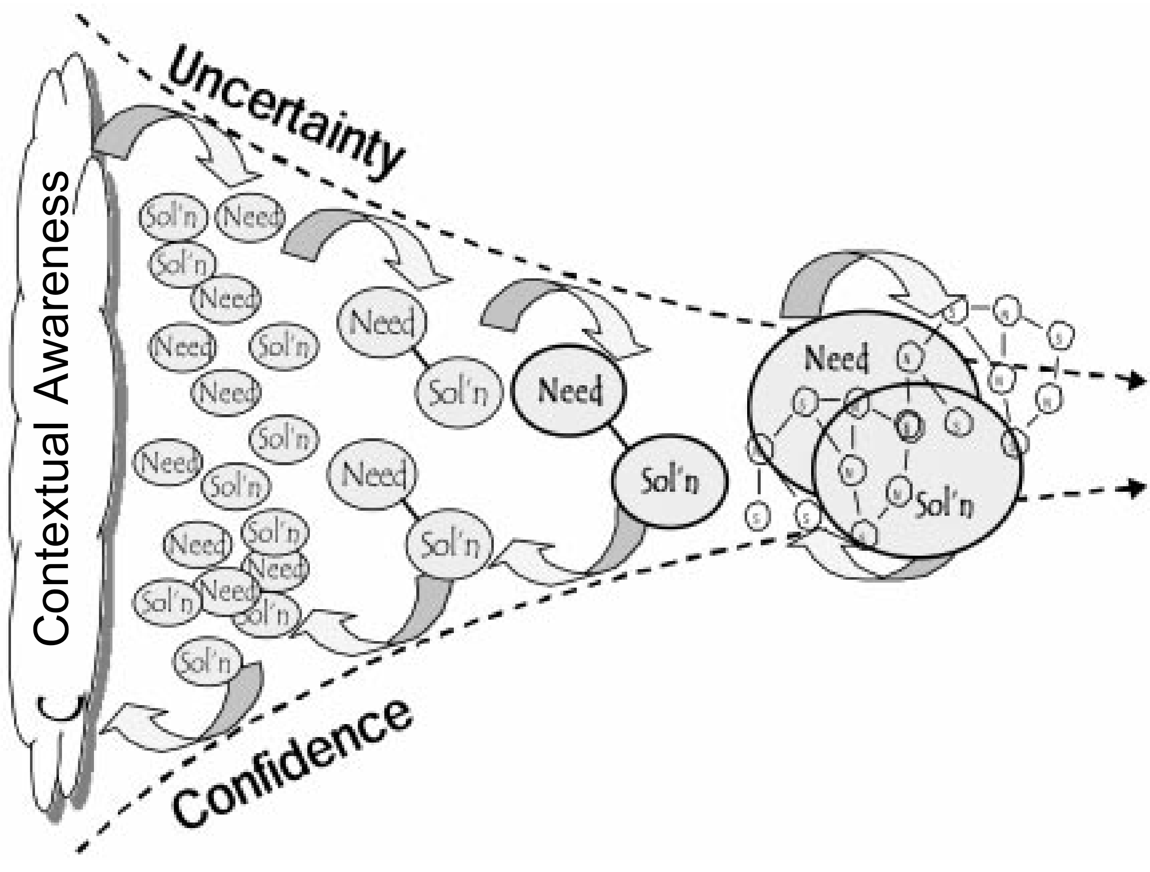

Fig. 5. Need–solution pair evolution presented as a Product Development Funnel with iteration to illustrate the true iterative nature of the design process. Notice that the process begins with superior awareness of a given context. This enables the greatest potential creation of a compelling need–solution pair.

approaches center on the notion of engineering problem-solving. When students are introduced to problem-solving in their academic training, the problem statement is typically explicit or mature. Accreditation is pushing towards training students to design for 'ill-defined' problems, but, by definition, these are still known and defined problems. Product designers deal with the comparably fuzzier situation of discovering and fulfilling a need. In this situation, the designer must cope with a more ambiguous situation than traditional problem-solving scenarios. This assertion assumes that the first problem focused upon may not be the most compelling need to be addressed. Traditional engineering approaches give the engineering designer responsibility and control over the development of the solution. In an innovative design approach, the engineering designer now has responsibility for the development of both compelling needs and solutions. As such, we extend the notion of problem–solution co-evolution into the realm of need–solution co-evolution.

Need–solution pairs as an innovation. Feland proposed that designers are most innovative when they develop compelling couplings of needs and solutions, as defined in Fig. 5 [11]. This assertion is based on extensive ethnographic studies of some of the most noted product designer firms in the world as well as a few Silicon Valley start-ups. This notion is further supported by Adams *et al.* [10] in their experiments with novice and expert designers. Adams found, during the development of design concepts, that not only did the experts iterate more between problems and solutions but they were also more likely to couple 'problem and solution elements.' In an effort to be more specific on the nature of needs and solutions in this framework, the following definitions are used. A *need* is defined as a perceived gap between a person or organization's present state and their desired state. The stakeholder of these needs may not explicitly state them as such. Methods such as surveys and customer interviews have proven not to be as effective as ethnographic methods of discovering latent user needs. Many times the user is not aware of their most compelling needs. *Solutions* are creations that enable a transition from the present state to the desired state, bridging the perceived gap, as illustrated in Fig. 4.

Building on this notion of innovative products as compelling need–solution pairs, we can quickly apply this model in the understanding of recent product releases. The most poignant example is that of Dean Kamen's Segway Personal Transporter (www.segway.com). The Segway is a marvel of modern engineering. Without a doubt it is a compelling technical solution. Unfortunately, the need is not as compelling. The gap between the present state and the desired state perceived by Kamen is much wider than the rest of society perceives. For another example, we can look to the Listerine Pocket Paks (www.listerine.com). Pfizer created a way for people to get fresh Listerine breath outside the bathroom. They designed the Pocket Paks as a portable solution—one small enough to fit into a jeans change pocket. By coupling a compelling need and a creative solution, Listerine Pocket Paks have been a run away hit—evoking multiple copycats and opening the door to a whole new category of portable healthcare products.

Apply need–solution thinking to new product development. This new model is used to create a new version of Wheelwright and Clark's Product Development Funnel [12]. This version of the funnel represents the decreasing uncertainty as the enterprise moves through the various stages of product development, as well as the increasing confidence in the success of the product in the marketplace. As uncertainty decreases and confidence grows, the realm of potential need–solution pairs is narrowed to one compelling coupling that eventually transitions through the remainder of the product development process into the customer's hands.

With this framework of need–solution pairs, we can see the benefits designers bring to New Product Development as brokers of needs and solutions. Traditionally, engineering designers are trained to begin with a high-level need–solution pair and then to iteration of the solution until a robust solution is obtained to release to the market. Using the need–solution pair framework, it becomes apparent to the practicing designer that both the needs and solutions are part of their responsibility.

Innovation impact map

With the need–solution pairing process perspective, we have built a model within which to frame opportunities identified during this process. The innovation impact map [9] assists in making a qualitative assessment of the potential market impact and success of a particular pairing of need and solution. The innovation impact map utilizes an assessment framework that explores the quality of life improvements afforded by the innovation, the number of entities impacted by the innovation, as well as the ripple effects of the impact through the value chain. Within this construct, innovations are modeled as networks of need–solution pairs. An automobile is a system of many solutions addressing many needs. These networks are mapped against the three axes of the innovation impact map to assess or explain market potential. Fig. 6 reveals the innovation impact map (IIM) and its three axes of assessment.

The primary axis is the quality of life benefits provided by the need–solution pair. A cure for a terminal disease would have a larger impact than an improvement to the life of light bulbs. The second axis is an assessment of the number of entities impacted. These entities could be people, organizations, or systems, such as HR managers, fast-food restaurants, or servers. The final axis is

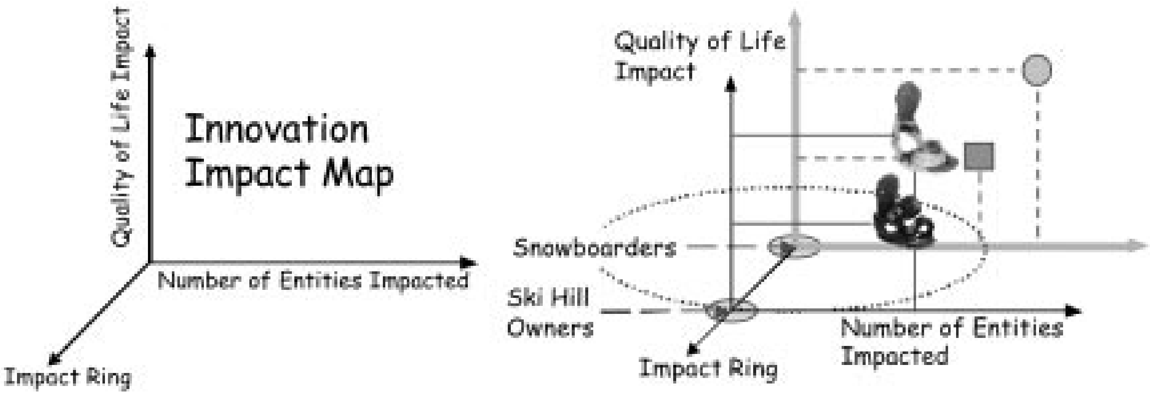

Fig. 6. The Innovation Impact Map detailing the three axes of assessment, Quality of Life Improvement, Number of Entities Impacted, as well as the Impact Ring. The figure on the right shows an example using recent innovations in snowboard bindings.

the 'impact ring'. Imagine the innovation as a rock tossed into a pond. There are rings that ripple from the point of impact. For example, a reduction in the cost of accelerometers used in airbag systems would allow the automotive industry to include airbags in all of their models. The initial impact ring is with the automotive companies. The second impact ring would be the automotive dealers that can use this new safety feature to increase sales against their competitors. The last impact ring is the automobile owner, who has increased his/her chances of surviving a major automobile accident. The innovation impact map utilizes near peer comparisons for the assessment of the impact the innovation could have. This allows for contextually sensitive assessment of the opportunity. One would not compare the Internet to the seat belt. They exist in drastically different contexts.

Innovation chain

Innovation cannot be treated as a serial or linear process. Rather, it is an active process of learning through trial and error. Networks, both digital and social, speed up the innovation process by connecting people across boundaries and accelerating learning. However, the right tools and models can facilitate and speed up this process by recognizing and supporting the key steps in the innovation process itself. The Stanford Center for Design Research, in collaboration with the Institute for the Future, has developed a staged model of innovation, called the 'innovation chain'. The innovation chain in Fig. 7 illustrates the evolution of an innovation as it matures, as well as the transitions between the stages of innovation.

The innovation chain represents the evolutions of innovation as well as the transitions necessary to

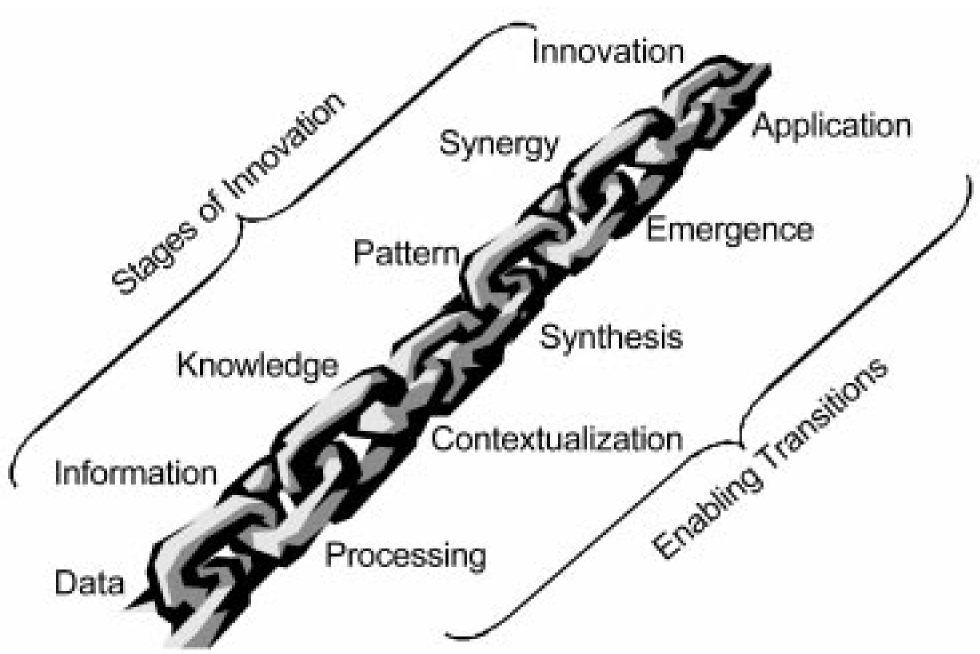

Fig. 7. The 'innovation chain' is a taxonomy of the various evolutionary stages of innovation and the corresponding actions associated with transition from one stage to the other.

evolve the growing innovation to the next stage. This taxonomy of innovation becomes pertinent to this discussion when used to classify current collaborative technologies. Existing Internet-based collaboration tools assist in the realm, from data to information, with some advanced systems touting the ability to contextualize information into the knowledge realm. The support of these stages of innovation is indeed critical and necessary for the eventual harvesting of innovations. Pattern, synergy, and innovation require the alignment of beliefs, the strength of trust, and a shared language across formal and informal networks. These last stages of innovation development are the most difficult, as they rely heavily on tacit knowledge and rich human interaction.

CDE PROGRAM STRUCTURE

CDE is intended to fill the curricular gap demonstrated in Fig. 2 and assist those that benefit from the program in consistently crossing the Innovation Fence. The program has influences across Bachelor's, Master's, and Ph.D. degrees.

Stages of student development

The Comprehensive Design program creates future designers through a three-stage process. As students move through the program, they successively move through the Apprentice, Mentor, and Leader Phases, shown in Fig. 8. The result of this program at all levels is an engineer who is both an expert and a comprehensive designer—someone with the ability to 'think' and 'do'. This designer looks across disciplines, roles and organizations to imagine, define and create new and innovative solutions. In order to achieve this, the Comprehensive Design program exists as one cohesive education experience in which each student—undergraduate through doctorate—works through a series of learning stages. These stages allow the student to develop the engineering knowledge required at progressively more advanced levels, while learning the additional knowledge and skills in which to contextualize, facilitate, accelerate, and lead innovation. The following is a description of the three stages of progression in the program and the accompanying academic degrees.

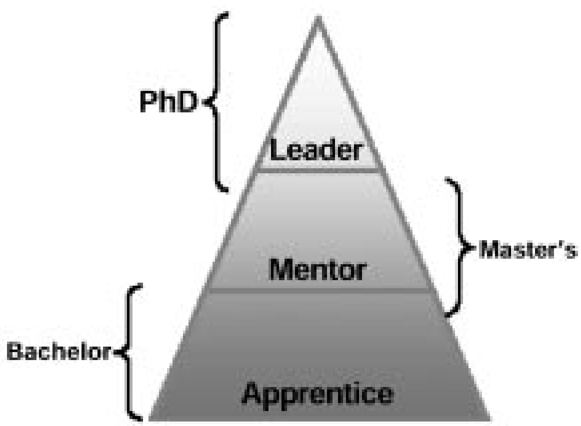

Fig. 8. Diagram showing the progression of student skills and correlation to academic programs. Each level is a balance between thinking and doing, utilizing active reflection as a method of honing the designer's skills during their progression through the program.

Apprentice phase. The 'apprentice phase' is a period of preliminary preparation for doctoral-level work prior to full acceptance into the doctoral program. The focus is on mastery of the design process and the intellectual discipline that is necessary for inquiry into the principles, methods, and products of design. This phase is normally two years in length, requiring 60 credit hours—the equivalent of a Master's degree in the School of Engineering. The length of this phase is flexible, depending on the level of formal preparation or experience of the entering student.

The student will participate in a number of team-based project classes during this phase, as well as having the opportunity for industry-based team design. Through this work the student will choose one of the projects to continue with a mentor or faculty member, developing initial conceptual thinking in one of the three areas of practice—Interaction Design, Product Design or Theory & Methods.

At the end of this phase, there will be a review of the student's progress by two faculty and two mentors (or leaders) from the Comprehensive Design program. The student will prepare a strategic thinking paper that describes the area of inquiry that will be the focus of his/her doctoral work, using the lens of fact, patterns and cumulative history. Mentors with whom the student has worked will be asked to give a brief assessment of performance and a recommendation on whether the student should continue in the doctoral program. Faculty members will review the input of the mentors, along with collecting assessments from other faculty and industry partners. As an outcome, the student is either allowed to continue or asked to terminate further studies toward the doctorate.

Mentor phase. In the 'mentor phase' of study, the student is expected to complete further formal coursework that has general or specific relevance to the area of inquiry that will be the focus of the dissertation. Course options are deliberately flexible, allowing a student and faculty member to plan work across disciplines. (For example, a student in Interaction Design could plan courses that are coordinated with the doctorate in HCI, including Computer Science and social and behavioral science courses.) Work in this phase ensures that a student is qualified to begin original inquiry leading to the development and completion of a dissertation. This phase of study normally requires 36 credit hours and culminates in a Ph.D. qualifying examination and a formal leadership proposal.

Leader phase. In the 'leader phase', the student is expected to lead a Comprehensive Design program with industry sponsorship, and document, write, and defend a dissertation on the thinking and methods used. Depending on the nature of the research problem, the final phase of work may be one or two years. The precise nature of the dissertation will depend on the industry problem that the student works on. In some cases, the dissertation may be a traditional written document, following the model of design, research and production in other fields. In other cases, the dissertation may be a combination of a written document and a demonstration design project, with accompanying process documentation. The dissertation must be an original contribution to the systematic understanding of design principles and their embodiment in the methods of comprehensive design. The doctoral dissertation is a demonstration of design ability and an original inquiry into the nature of comprehensive design in theory, history, or criticism, possibly with a demonstration project that illustrates the principles and methods that are the central concern of doctoral inquiry. The decision about whether a demonstration project should be part of the dissertation is reached through discussion with the student's dissertation adviser and dissertation committee.

The what, how, why and when progression

Students are now faced with an increasingly complex world. Whether joining industry as a practicing engineer, pursuing a research position, or continuing on for further education, the 21st century requires students to possess a broader knowledge of processes and activities within their own field and related areas. Building from the knowledge-what learned during undergraduate education, the comprehensive design model is to help students at all levels to first appreciate, and later obtain, knowledge-how, -why, and -when, again within their field and in related areas. This model builds on recent trends in higher education and industry to develop learning practices and technology that move beyond data and information to introduce concepts of tacit knowledge, patternmaking and synergy. The comprehensive design program teaches the facts that are required to practice as an engineer or technologist and extends this focus of developing the knowledge-how, -why and -when using theory and practice. As the student advances through their education, different stages of this knowledge progression are delivered at different times, motivating further study and creating a new model of life-long learning.

Theory and practice

The core of the Comprehensive Design Engineering curriculum is the belief that engineering education should be grounded in a balanced mastery of both theory and practice. Every degree area and level in the CDE curriculum is presented as an integrative educational experience through classroom learning, team-based development and industry practice. This approach couples traditional educational practice and theory with more practice-based experiences. This approach of practical, hands-on experience and reflective development is intended to enhance the learning experience, from undergraduate through doctoral learning. At the culmination of their degree work, undergraduate students will possess a strong engineering ability and a broader understanding of the complexity of today's engineering solutions. Graduates of the Master's program will leave with knowledge and an ability to practice that supports their experience and previous education along with a new understanding of mentoring and team-based engineering. And graduates of the doctoral program will enter academia or industry with a strong ability to lead, educate, extend the theoretical understanding of comprehensive design, and to be immersed in practice.

FUTURE PATHS OF STUDENTS

Given this balanced approach to their education, graduates of the Comprehensive Design Engineering program move into many varied files upon graduation, as highlighted in Fig. 9. Most of the graduates of the Bachelor's program receive an accredited engineering degree. This creates the opportunity for students to enter any of the traditional engineering professions as well as start their own ventures. The Master's program develops graduates to work at higher levels of responsibility and management. Ph.D. students can expect to function as professors, entrepreneurs, and Chief Technical Officers (CTO) of companies.

NEXT STEPS

The Comprehensive Design Engineering program is still in the early stages of development. The first course, Innovation with Emerging Technologies, was offered in the spring of 2002 with tremendous success. The program and the

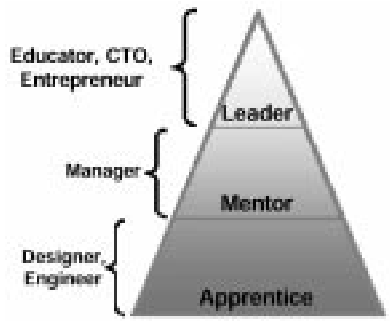

Fig. 9. The program diagram with the anticipated roles of the graduates of each tier of the Comprehensive Design Engineering program. The top tier seeks to fill the curricular gap in Fig. 2.

frameworks that support the program continue to evolve. By focusing on the intersection of technical, human, and business issues, the tools and methods being developed under CDE promise to enable participants in achieving consistent innovation.

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