# Fundamentals of a First-Year Engineering Design and Communication Course: Familiarization, Functionality and Testing

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## Introduction

There is a large body of pedagogy surrounding the use of a common design methodology in engineering. The well known description of the design process as a series of steps from problem identification, through conceptual design to detailed design has been a standard in engineering design courses of all levels for at least 50 years. The design process does indeed document the main components of successful design. However, the ability of engineering students to grasp the significance of the steps in the design process is not ideal. In fact, it might be said that employing the standard design process is much like playing the music of Mozart: Too hard for professionals but too easy for students. Even at the professional level, blind adherence to a set procedure for design too often results in the creation of inferior products[6]

Much of the literature describing the loss of engineering design skills, particularly in North America, focuses on the ways in which the process might be given meaning for the students of engineering design. It is our view that the great number of pedagogical devices, case studies and design projects that have been developed over the years to demonstrate the application of the traditional design process (with sporadic levels of success) is an indication that there may be a problem with the portrayal and implementation of the design process itself. In short, the design process makes sense when taking a retrospective view of a successful design. However, it breaks down when a novice attempts to apply the process to a real design project. For example, the first design process step of determining the problem is known by every designer to be the most difficult part of design and often occurs closer to the end of the actual design process than the beginning.

We have taken on the task of developing an approach to the design process that we refer to as the "Design Trinity" of Familiarization, Functionality and Testing. The design trinity, employed in an environment of participatory inquiry [13] is intended to engage the novice designer in a way that develops a sense and rigour to their design work. It is intended to occupy a mid-point between the "man-on-the street" approach (an endless cycle of build/fail) and the highly sophisticated use of successful design methodology.



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In this paper, we will briefly review some historical factors in order to highlight the fundamental problem with the traditional approach, followed by a description of the elements of the design trinity (Familiarization, Functionality, Testing) and an explanation of the implementation of the concepts. Implementation is more a matter of understanding the general philosophy of the course than isolated exercises. Therefore, implementation is viewed through the development of our approach to the rational paradigm and the practice of participative inquiry.

**Historical Perspectives**

We begin with the concept of engineering education as promulgated through the Grinter Report of 1955. The Grinter Report was the end result of a multi-year, US based commission into the current state and future goals of engineering education. The effect of the Grinter report was profound. In one stroke, the traditional, apprenticeship-style, hands on, shop focused, drawing and design oriented training of engineers was abandoned in favor the current math/science model of lecture, lab and tutorial. To put it bluntly, "Not anticipated were the downstream imbalances in academe that emphasized engineering science and analysis to the point of reductionism at the expense of design and integration"[1].

The framework for the teaching and learning of engineers was now built around what has been termed as a rigid methodology relying on "tame" problems and problem solving rather than the creative solution of open ended or "wicked" problems. The Tame problem is a term, coined by W.J. Rittel in his design lectures at the University of California, Berkeley[2]. In Rittel's view, math and science problems, which are comprised of clear, theoretically based textbook problems centered around formulaic manipulation, are "tame" problems because they rely on well traveled solution paths that always end up with the same answer. Design problems, however, Rittel[2] describes as "wicked" problems because there is no identifiable solution path or any concept of what the answer might be.

The Grinter report clearly identifies design problems and therefore their inherent wickedness as one of the cornerstones of the engineering profession. However, the entire post-Grinter curriculum shifted to the study of tame problems. Something was clearly amiss. By the time, the momentum of the changes being introduced through the wholesale adoption of the Grinter framework was far too advanced to redirect. The only course of action was to let the changes take place and to seek to revitalize design through isolated coursework. To this end a large number of design textbooks have been produced over the years in an effort to place design education within the lecture, tutorial, laboratory framework. However, despite the best efforts of a small but dedicated group of engineering academics, design has remained an afterthought in the training program of the engineer.

Now, in 2004, the problem of inadequate design training still exists and is proving to be very complex and difficult to solve. Although engineering accreditation boards are pushing strongly for major improvements in the teaching of design, the response from many institutions is less than heartfelt. At issue is the lack of a suitable response to the fact that the skills of the designer lie more in synthesis (bringing together different points of view) than in analysis, yet the training of the engineer is primarily in the area of analysis.

Therefore, the difficulty in developing adequate design skills is due in part to the failure to introduce both the skills of synthesis and the associated technical knowledge base[3] into the engineering curriculum. This is an easy statement to make and many engineering educators have gone to great lengths to develop methods for teaching synthesis within the current framework. However, the problem remains that the background of most engineering researchers and instructors has necessarily been in analysis. Therefore, the natural tendency is to merely paint over the existing analytical learning structure with synthesis concepts (problem identification, idea generation, concept development and evaluation). The end result is that the overall picture starts to look like one of design, but the underlying framework, fundamental assumptions and methods are still based on an analytical model. In order to get a fresh perspective on the necessary conditions for teaching and learning design, we must develop an approach that encourages synthesis as well as analysis.

Fortunately, as we examine the methodologies of non-engineering and even non-science disciplines, we find that, across disciplines, design problem spaces share many common features[4]. We also find that design problem spaces differ in significant ways from non-design problem spaces[2]. The design trinity was developed through a combination of design and synthesis concepts both inside and outside of engineering.

In this paper, we develop a pedagogy based on the concept of integration and synthesis. The design trinity leads to an integrative approach to engineering design problem spaces. Through the design trinity, the design process becomes less prescriptive and can be presented to the novice as core activities involved in the doing of design. Therefore, students are able to advance their design skill beyond the man-on-the-street approach through the learning and application of specific and fundamental techniques (Familiarizaiton, Functionality and Testing) and to attempt the integration through an iterative use of a small number of fundamental techniques.

## Familiarization (and the Problem with Rationality)

In practice, familiarization develops the notion of synthesis that requires novice engineering designers to learn how other people think (clients, end users, manufacturers, legislators as well as other types of problem solvers). When presented with a real world design problem, the first task of the student is, through discourse, to collect as many stories as possible from the key stakeholders in the design problem. The focus is not, as it is in the analytical approach, to define the problem. The first step is to simply assemble enough outside knowledge to form a basis for synthesis. Provided with an adequate supply of different viewpoints, the students understanding of the problem emerges indirectly. As time goes on, the well known stages of successful design will be realized, although not through a simple step by step process.

Familiarization requires the engineering designer to step back from the security of the traditional rational paradigm. which assumes that, with proper training, people can be entirely rational and make decisions based on logical argument. It claims that all design problems can be reduced to a fundamental set of constraints that can be worked through in a logical fashion resulting in a design solution that satisfies those constraints. Adherents to the traditional rational paradigm believe the path to a successful design is simply a matter of working through the constraints dictated by the problem itself. There are a finite number of design paths. Arguments for or against a particular design path are settled by the approach that provides the best quantitative response to those constraints. Therefore, many engineers consider design to be something other than a creative activity. This rational paradigm tends to be the default mode for students when presented with an open-ended design problem.

However, it is now clear that the traditional approach has has failed to advance the development of engineering design and perhaps the development of design in general. Even in architecture, for example, "most architectural educators think their task is to teach students how to design architecture according to conventionally formal mechanism"[5]. Empirical and rational scientific methodology may well be the guiding principle of the age, however, the act of creative design is the driving force behind advancement[6]. It is the dominance of rationality to the exclusion of other, more humanistic activities that is causing the problem[7]. The act of creative design is entirely human but not entirely rational, and according to Sternberg[8] even opposing design approaches share the view that good design seeks to reintegrate the human experience.
Continued adherence to the rational paradigm and the accompanying notion of the design process holds only the promise that society will continue to be plagued by inferior products[6]

Fisher[9] believes that the assumptions of the traditional rational paradigm limit our understanding of reason and rationality by separating logic from everyday discourse. Design spaces require a forum for an integration of many stories or ways of knowing about the world. Without discourse, this crucial synthesis cannot take place. In fact, Rittel[2] describes the act of design as the telling of a story.

Therefore, engineering design can and should be something more than an analytical, rational process. Of course, we cannot ignore the importance of rationality, analysis and process. Fisher does not deny reason and rationality, as understood in the traditional rational paradigm and does not think that such wide ranging discourse, or as he describes it "the narrative paradigm" will or should supplant the rational[9]. Rather he seeks to reconstitute rationality to offer another story about "truth, knowledge and reality"[10].Fisher offers an alternative to the notion that communication must be argumentative to be considered rational and paves the way for a perspective that includes values and emotions, as well as aesthetic considerations, as motivating elements of social and intellectual life[11].

Technical rationality contributes to the well known "over the wall" problem in enginering. Here, the focus of the engineer designer is restricted to solving the problem according to correct theory as s/he understands it rather than developing a complete picture of the problem from a variety of different points of view. The assumption has been, as it is in the rational and analytical classroom, that correct design theory will yield correct design practice. However, assumption fails in the design classroom[12]. The theoretical approach to design provides a series of prescriptive steps which seem to encapsulate the workings of the designer's mind. However, the steps are only evident when the design is complete. To follow those same steps in the next design will generally not be successful because the story and the problem behind the design will necessarily be different. In this way, correct theory can be a threat to design education as the student of design tries to force a fit between the prescriptive (tame) methodology and the wickedness of the design problem.

Rather, the novice designer must be encouraged to recognize and exploit the notion that "Bringing different points of view together and trying to create a shared understanding among all stakeholders can lead to new insights, new ideas and new artifacts"[10]. In other words, it will be the proper development and synthesis of knowledge from all participants rather than correct design theory that will lead to effective design. The practice of developing of these new insights, ideas and artifacts we refer to as "familiarization".

**Functionality**

The challenge for the designer is to design according to what the design is supposed to accomplish rather than what the design is going to look like. This we call addressing the "functionality" of the design. This is probably the most difficult aspect of design for both the professional and the novice. To use the example of scissors, the functionality of scissors might initially be thought to be "to cut". However, there are a limited number of ways to "cut". The solution space for the function of cutting is rather limited. We can further refine the functionality to be "material separation". Now the solution space is greatly expanded to include tearing, burning, sawing, melting, milling, filing, grinding and so on. Therefore, any design problem has a multitude of possible solutions that arise from a proper understanding of the functionality of the design and its many components. This is similar to the concept of the morphological matrix although functionality is the platform from which the morphological matrix grows.

Understanding functionality and communicating it to the client is critical to both the acceptance and the success of any design. Functionality provides a critical communication link between what the customer wants and how the engineering designer will achieve the desired outcome. A great many designers, novice and professional, make the mistake of presenting their design solution fait accompli to the client only to be told the client had a completely different solution in mind. It is the job of the designer to create an environment in which both client and designer walk hand in hand toward the solution. In other words, a sense of community must be developed around the evolution of the solution. The presence of a real world client makes this difficult because most clients have a picture in their mind of what a solution to their problem might look like. However, the client is likely to be wrong with respect to both the problem and the solution. It is the job of the designer to establish the basic functionality of the required design and communicate that functionality to the client by integrating the knowledge gleaned from familiarization together with his/her analytical abilities. In the traditional classroom, the instructor does this work for the student by isolating exactly what function the student will address. Unfortunately, sanitizing the problem in this way removes it from the design problem space and places it firmly within the analytical problem space. In recent work with our graduate students, one real world design project client identified a design problem as the development of a parking brake for wheel chairs used in geriatric care facilities. The graduate student did his due diligence in familiarization and discovered the problem was not the lack of a parking brake, but the prevalence of injuries due to patients tipping the wheelchair over. However, the client wanted a parking brake. Once the student re-focused the problem to be that of stability, the client was able to see that the concern over patient injury was better addressed through preventing the tipping of wheelchairs rather than through the development of a parking brake.

**Testing (or Telling a Convincing Story)**

Testing, the third component of the design trinity provides the foundation for design development. A primary foundation of the design courses is the concept of justification. We give little importance to the correctness of any given design and focus instead on guiding the students to justify the development of their design. A convincing design approach makes extensive use of testing as a quantitative assessment of the developing design. The essence of the concept is that students test their way through the development and modification of their own ideas and re-assess, re-test and re-design as they continue to receive, develop and refine the endless stream of new information. At every stage of the design experience, the student teams must develop and defend their design approach by developing their own tests for effectiveness.

While testing is the bread and butter of the researcher and of the designer, students have difficult time with the concept since their experience with testing is primarily that of opening the laboratory instruction book and following the instructions. When faced with the prospect of developing their own tests to assess the functionality of their design, most are stymied at first by the lack of the instruction book. The fallback position becomes that of justifying their design decisions through the “motherhood and apple pie” method. For example, “We decided to go with this design because we think it is cheaper” rather than “As a result of our testing criteria for cost versus performance, we selected this design”.

As they struggle to develop their own tests students are inhibited by the fact that they have only seen well developed, tried and true laboratory tests. It takes a considerable time before they begin to understand that if they make use of the knowledge created through familiarization and functionality, the development of a suitable set of tests will follow quite naturally. Something as simple as counting the number of times balls made from different materials bounce on a floor is a perfectly legitimate test of the function of elasticity. However, it requires that the students have, through familiarization and functionality, determined that elasticity of the ball and/or material is a central function for their design.

Of course, there is no linear pathway through these knowledge developments. The real path is an ever-expanding cycle of revisiting, rethinking, expanding and reintegrating of the design trinity. This iterative process is repeated at every stage of their design training. Through this iterative approach, the features of engineering design that are common within the profession (targets, specifications, design for X, functionality) are developed in a process of negotiation between the students, the clients and the instructors. The knowledge of the students about design and about the design of their particular project is developed through the development of the design trinity.

**Platform for Integration**

In order to keep the student firmly within the design problem space, we use the concept of participative inquiry in conjunction with the design trinity. The job of the students is to develop their own sense of the functionality of the design in the absence of a "right answer". As a result, both students and instructors must adopt non-traditional roles within the design classroom[14]. Rather than sanitizing the problem/approach, the instructor relinquishes the role of the all knowing sage and instead becomes a partner with the students in the creation of new knowledge surrounding the design problem. The identifying characteristic of this type of participatory learning environment is a higher level of discomfort for the students since there is not the usual guidance to the right answer from the instructors. Initially at least, there is a great deal of uncertainty since, in the absence of textbook examples, the students are unsure how their efforts will be received. However, in design, "if you are comfortable, you are not doing design"[15]. The goal is to support the students in their roles as knowledge makers while maintaining a necessary level of discomfort and uncertainty to allow the students to participate in that knowledge making.

Participative inquiry illuminates the process of participation in a community in which all members, instructors as well as students, learn and participate in the creation of new interdisciplinary knowledge. Inquiry is a fact of life in the design classroom where, if the work is real design work, every design problem is unique and has never been solved before.

From the standpoint of participative inquiry, the scientific perspective while offering a "critical public testing of what is taken as knowledge"[13], also places the inquirer "firmly outside and separate from the subject of his or her inquiry"[13]. Participative Inquiry proposes an alternative worldview in which people are seen as "co-creating their reality through participation"[13]. That is, through the sharing of their "experience, their imagination and intuition, their thinking and their action"[13], members participate in the construction of new interdisciplinary knowledge.

Students expecting a traditional relationship with the instructor as all knowing are uncomfortable both with their responsibility to create knowledge and with the absence of the security that the instructor will always have the answer. This is particularly true in a very large class. We have had participatory classrooms from 3 to 600 students. It is possible to coax a class of even 130 students to engage in inquiry and work outside of their comfort zone in the normal class environment. For a class of 600 however, a great deal of public relations and communication work is required to keep the discomfort at a manageable level.

Nonetheless, even with very large classes, participative inquiry has an interesting transformative aspect. Participative inquiry offers a window to the process of knowledge development that is closely linked to the working world as opposed to the academic world. Therefore, the experience gained can be transformative in that the intangible ways of the working world become part of the learning. In the design classroom, we have witnessed this many times as the students come to a realization that there are many issues surrounding a design problem that initially do not seem to be directly related to design. In one recent example, our students had to cope with a very tight time-line for the ordering, delivery and testing of prototype materials for a design of speed skating crash pads. The successful design teams adjusted their design constraints to include the tight time frame. The less successful design teams could not get past their expectation that the instructors should be sanitizing the wickedness out of the design problem for them. Subsequently, a lot of time was wasted waiting for someone to make it right.

Hopefully, for all of the students, the light eventually goes on (sometimes years later) and they recognize that coping with the never ending stream of new information is the heart and soul of design. If this transformative experience can be acquired early on in the education of the engineer, the potential for the student to develop into a creative problem solver is greatly enhanced. This is also the very glue that holds the ideas of familiarization, functionality and testing together; students must determine the most appropriate application of these concepts and in doing so provide intrinsic justification. The final result of the design experience is intended to be a unique solution to a real world design problem that is well justified through the participative inquiry undertaken by the students.

**Application and Results**

The design lab activities are carefully constructed to encourage the students to learn and make use of the design trinity in order to build a convincing story or argument around the development of their design. The introduction of the design trinity is structured to allow the students to focus on one component at a time, while maintaining the importance of their interdependence, before allowing them to apply these concepts concurrently to several projects.

Familiarization is introduced through a two-week project focused on sustainable design in the developing world. The latest project asked the students to develop a plan for implementing water, sewer, electricity or heating in a small village in southern India. This type of project required the students to spend a significant amount of time familiarizing themselves with geography, resources available, and religious, cultural and local customs. A development project is very well suited to introducing familiarization because the students generally have very little knowledge of the area and any solution must be sensitive to local resources and customs. At the end of the first week of the project, the students must prepare an oral presentation detailing the results of their familiarization and their corresponding design criteria. At the end of the second week groups prepare a written report outlining their design concepts. Their grade is determined by how well they integrate the constraints (found only through familiarization) into their design. It is very easy to determine, from the oral and written presentations, if the students have understood the role of familiarization and have done sufficient investigation. Students who do not understand familiarization will propose unrealistic solutions, such as microwaves or furnaces.

The concept of functionality is perhaps the most difficult for students to understand. The students' initial exposure to functionality is done through an exercise where they are given a lego model of a mechanism or device. Examples of models we have used are a pump jack, balance scale, centrifugal governor and scissor jack. Groups are then asked to decompose the functions of the model and to describe the model using functions only. They are not to describe the appearance of the model, only what it does. Groups with different models then trade descriptions and build the unknown model using only the functional description. What the students usually find is that the model built from the functional description bears little resemblance to the original model. This is exactly the result we hope for, as it reinforces that functionality is what something does, not what it looks like. Students are assessed on the completeness of their functional decomposition, specifically describing functions and not appearance.

Testing is introduced through a project where the students are asked to dismantle an object or device in order to evaluate and report on the primary design functions the designer had addressed. In addition, they are asked to develop, execute and report on a test for two of the design criteria they have assessed. The evaluation of the deliverables (oral and written reports) is based on how well the students justify their decisions and not on whether they were correct in their answers since a correct answer does not exist. They are encouraged to provide evidence to establish their report as credible.

After the introduction of the design trinity, the students are given one five-week, one six-week and one three-month design projects. The students are expected to apply familiarization, functionality and testing to their projects. Any design decision is expected to have the design trinity at its foundation. We do not, however, expect the students to master these concepts immediately. By giving the students multiple projects they have the opportunity to learn from their mistakes and to show continuous improvement in their application of the design trinity.

The effectiveness of this approach has been demonstrated in several ways. Perhaps the most compelling measure comes from a student evaluation administered at the end of the year. As part of this evaluation students are asked to assess their own development in a number of skills. The results from the 2003 self-assessment are shown in Figure 1. The skills most closely associated to the design trinity are Innovation in Design and Assessing Design Solutions. Figure 1 shows that approximately 78% of students felt they developed design innovation skills and 69% of students are able to assess design solutions. These results can be attributed in large part to the application of the design trinity.

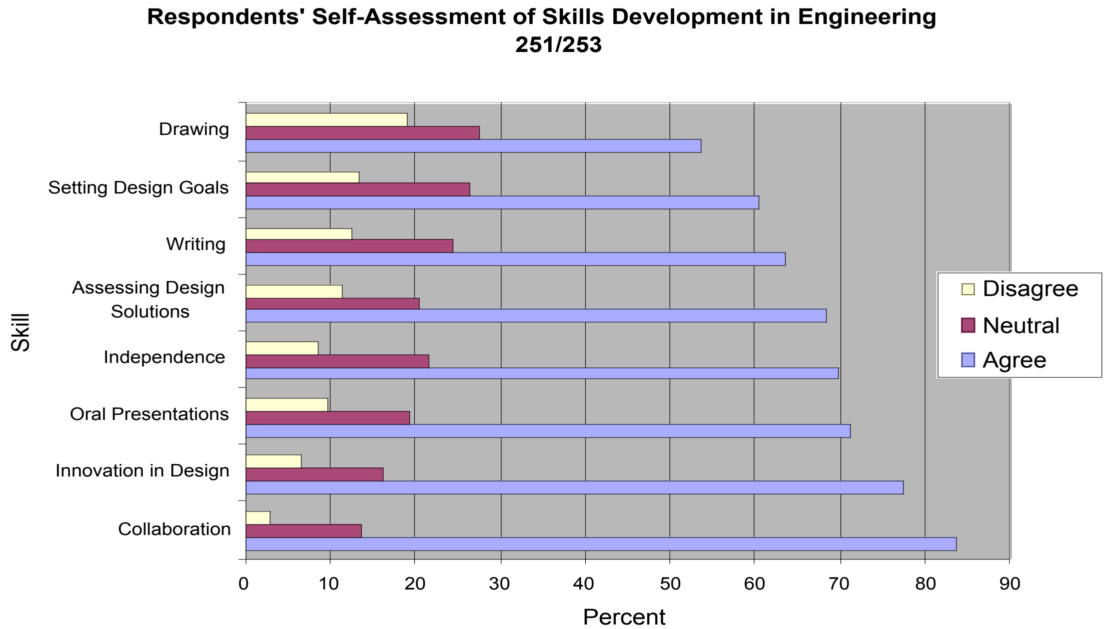


Figure 1 Respondents Self-Assessment of Skills Development in First Year Design Course

How these results would compare to a course using a traditional design approach is difficult to assess. The evaluation used to produce Figure 1 was not administered prior to our introduction of the design trinity. Perhaps the best comparison would be the fact that the former course, which presented a traditional design methodology, was abandoned entirely in favour of the design trinity approach.

**Conclusion**

In order to solve the current problem of a shrinking resource pool of engineering designers/innovators, we recognize the need to reintegrate the human experience into the practice of engineering design. The development of the design trinity (familiarization, functionality, testing) and its use in an environment of participative inquiry has enabled our first year engineering design and communication class of 600 to develop creative solutions to real world, open-ended problems.

An environment that nurtures design, innovation and creative problem solving must necessarily be a participatory, social environment. The social environment requires participants to engage discourse, listening to the points of view of others and the negotiation of what counts as important knowledge for the given design problem. As a result, engineering design instruction becomes more a matter of creating the necessary creative environment creative and less a matter of dictating correct design theory. Six years of experience in developing an approach to the teaching and learning of engineering design at the University of Calgary, allows us to say with confidence that the design trinity, used in conjunction with participative inquiry is an effective approach to creative problem solving.

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## Biographies

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DARYL CASWELL is a professional Engineer, professional Musician and a Designer and Manufacturer of tools for the music industry. He has thirty years of experience as a teacher in engineering and music. Dr. Caswell also uses his multi-disciplinary background in the field of acoustics as well as in design and engineering education.

ROD FAUVEL has been a professor in Mechanical & Manufacturing Engineering at the University of Calgary since 1981. He has worked in construction, oil production, aviation and mining. His current research focuses on design methodology and engineering education. He continues to be an active designer and is involved in many ongoing projects.

DIANE DOUGLAS is a writer and art historian. She taught art history for ten years at the Alberta College of Art and Design before moving to the University of Calgary in 1991 to teach communications in the faculty of Communication and Culture. She co-authored *The Drawing Process* (Prentice Hall, 1993) with U of C art professor Dirk van Wyk.

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