Delta Design INSTRUCTOR'S GUIDE

1. Introduction

Delta Design is a team exercise created for undergraduate education in engineering. It requires approximately 3-4 hours — all in one sitting or spread out over several session. The major goal of the exercise is to have students learn — by doing — that design involves, not just technical expertise, but extensive negotiation among specialists working to reconcile divergent views and conflicting agendas.

Participants learn that design in teams -- the kind of design they will do most often in the workplace -- is a social process as well as a technical process, and that excellence in design requires simultaneous attention to both. Along the way, the exercise imparts or reinforces basic knowledge about the modeling of physical systems, the application of heuristic reasoning, the costing of different options and the like. It has the additional benefit of being fun.

The exercise replicates in microcosm the sometimes uncomfortable reality that no matter how hard designers on a team try to work independently, to decompose a task into separate phases, or to define clean interfaces, they still find it impossible to avoid the intersection of interests, the framing of tradeoffs, and the compromising of requirements, specifications, and goals. Delta Design brings these characteristics of process front and center with deliberate collisions between domains and a task so tightly coupled that design changes in any dimension affect all others. It does so to help students understand the true nature of engineering design, to give them a feel for what engineers really do.[1]

Students assume and learn one of four expert roles, join a team in which all roles are represented, and design together a residence for the inhabitants of an imaginary world. The roles are ***architect, project manager, structural engineer***, and ***thermal engineer***. Their domains are not as simple as might be inferred from an exercise engaged with ordinary equilateral triangles. Nor are the tensions and tradeoffs between them straight forward; the artificial design space has been constructed to capture, yet clarify, the kinds of tradeoffs that exist in the real world of engineering design.

1. For a fuller discussion of design process by the author of Delta Design, see Louis L. Bucciarelli, **Designing Engineers**, MIT Press, 1994.

The design itself, an assemblage of elemental components called *deltas* that acquire varied aesthetic, fiscal, structural and thermal characteristics when assembled, must satisfy performance criteria in each dimension, for each role. Teams whose members get beyond mastery of individual domains and develop effective strategies for working together can produce designs that meet or exceed spec. Dysfunctional groups have more difficulty, even if individual members are exceptionally gifted in their specialties. Participants are keenly aware of this by the end of the exercise, when they present their work to the class.

While the central lessons of Delta Design are unchangeable, the instructor nevertheless retains considerable leeway to tailor the exercise as he or she sees fit, to teach different lessons about design. This tailoring can be done by tinkering with the "science" of the design space, or simply by establishing context with introductory remarks, post-exercise discussion, and the point where the exercise is embedded in the syllabus. Possible variations include:

- Design constraints and performance specifications can be adjusted to make tradeoffs tight and complex or they can be relaxed to avoid them. Multiple plays of the exercise under these different conditions, either in time by the same group or simultaneously by more than one group, provides substance for comparison, discussion and learning.

- The exercise can stress the need to think broadly about design, to realize that fulfilling one's own obligations on a project is not sufficient to ensure a good outcome. One must work with, and trust in, others.

- It can serve as a basis for a discussion of the problem of evaluating different design outcomes: What is a "good" design? Is quality a matter of meeting specs at minimum cost? What is a "robust" design? What if two out of four participants are satisfied but the others uncomfortable with their contribution? Does the integrity, enthusiasm and vitality of the design *process* tell us anything about the quality of a design *product*?

- Delta Design can be used to emphasize communication skills, both during interactive play and in post-play presentation of group results. In the process of designing, participants realize the need to provide reasons for their recommended design moves clearly and succinctly and in terms the others, not schooled in their specialty, can understand.

- Ideally, multiple teams play the game simultaneously and when done, present their design to the others. The instructor can use the occasion to critique communication skills.[1]

This is a list of some of the educational goals that can be addressed with the Delta Design. It is by no means an exhaustive one, as in the authors' experience, play corresponds so closely to design in the "real world" that participants and observers alike add new suggestions and observations after each round. At the same time, it is game-like in many respects — in asking participants to play a role, in the intensity with which they do so, in the competitive quality of their interactions, and in competition between teams.

1. The exercise works best if there is more than one team engaged in the play. Five to ten teams going at it in the same room engenders a lively session.

2. The Design Task

The task assigned in Delta Design is described as the design of a residence for the inhabitants of an imaginary world, but more precisely, it is to assemble red and blue triangles into an envelope anchored in two-dimensional space.

The triangles, called "deltas", generate and/or conduct and/or radiate heat, are acted upon by gravity, and cost money, as does the glue that holds them together. The envelope must be spacious, structurally sound, thermally balanced, aesthetically pleasing, and able to be constructed within budget and schedule. The task is a challenge as well as abstract.

It was made abstract for several reasons, the most general being to moot the previous experience of participants and generate a "pure" design process untainted by prior knowledge, a design process in which the design product is equally unfamiliar to all. The abstraction controls the context in which participants work and emphasizes the point that while there is one design, different participants have very different visions of what it is and what it means.

Abstractness also allows participants with differing backgrounds and levels of experience to interpret and read into the exercise different things. The exercise has been engaged by undergraduates, (freshmen to seniors), graduate students, and practicing engineers alike, with different dynamics but equal satisfaction. While the abstractness of the task disconnects it from the real world, the open form of the design problem is all too familiar to practicing designers. There is no single "right answer," nor even a finite set of solutions. There are specifications to meet, and assorted ways to assess performance, but the authors themselves have little idea just how good a design a team can create.

The design task is also malleable, in the sense that, as previously discussed, the instructor can modify it by changing either the context or the specifications. We caution that changing the specs should not be done lightly, lest the task become too easy or too difficult, and that instructors should observe a few rounds before doing so. On the other hand, we have left a powerful "lever", the overhead multiplication factor, completely at the instructor's discretion. This factor, which the project manager needs to know at the outset, should be specified somewhere between 1.0 and 2.0. At the lower bound, coming in under budget is trivial, while at the upper bound cost becomes a heavy constraint. We have occasionally relaxed or tightened this factor midway through the exercise when teams appear to be paying too much or too little attention to cost.

For more information on the design task, refer to the introductory handout for all participants and the primers for each role.

3. The Exercise

Delta Design has four phases requiring a total time commitment of three to four hours. In the first phase, participants are given an overview of the exercise and an introductory handout to read, then assigned and taught their roles. In the second phase, teams design. In the third, they present and defend their work,. The fourth and final phase is for review and discussion.

The instructor should allow an hour for the first stage, or alternately, assign roles and distribute materials beforehand; instructors taking this approach should request that students not discuss their roles before the actual act of designing begins.

One hour should be reserved for design, with a ten minute warning given near the end of the hour so that teams can finalize their designs and prepare for presentation. Five minutes per team is sufficient for presentation. A matrix summary of each team's performance measures is useful for comparison purposes — but make sure the architectural qualities of the design are included in this comparison.

Closing discussion can last from 10 to 30 minutes. These are recommended minimums; any or all can be lengthened at the instructor's discretion.

3.1 Instruction

Participants need to learn their roles. Training is done best by having four tutors, one for each role, take the students aside after they have familiarized themselves with their primers, to indoctrinate them in the lore of their trade. The tutors should lead discussion, answer questions, and basically conduct a short course in project management, structural mechanics, or the like. The fidelity of the design phase is deeply affected by the depth of knowledge and strength of role identification imparted during training, so don't skimp; as in life, the more training the better.

Thermal engineers must learn to estimate average temperature. The method described in the primer works quite well and is relatively straightforward once the notions of free, outward-pointing, node and radiating length are grasped. Estimating the temperature of individual deltas, on the other hand — whether too hot or too cold — is a cruder, less sure affair. The primer describes some situations to avoid but these are not absolute nor do they represent all cases where one could get into trouble. The player must develop and appropriate the information provided for their own use.

Structural engineers need to know the importance of symmetry in distributing gravitational loads. They should see that the best situation is when both support points carry the same load. This will be the case if the two are equidistant (remember the skewed measure) from a line running in the direction of the inplane gravitational force passing through the cluster's center of gravity. Estimating internal moments is more difficult but the primer provides the means to carry this out. Having the student experiment with a configuration of deltas layed out on the grid, exploring with the role instructor, the magnitude of the internal moment as one moves around the structure is a very useful, warm-up exercise.

Project managers have to figure out which cost components are critical, what will make or break the schedule. The instructions, tables and graphs in the primer provide the basis for these calculations. Note that though the project manager has responsibility for cost and schedule but is not "in charge" of the team. During training, make sure that they understand this point so that team leadership style and authority relationships can develop naturally during the exercise.

Architects need to develop confidence in their knowledge that they know what constitutes a good design. The individual playing this role, the "softest" in an otherwise "hard" exercise, needs to develop an aesthetic for the imaginary world. The primer provides a start, but more elaboration of what the clients value or disdain should be encouraged. This can be spontaneously constructed by the player, or representative "good" and "bad" designs might be provided. It is essential that the architect speak confidently when confronted with the more instrumental mindsets of other participants. During the design stage, architects that rely more on "hard" measures from the primer than on their innate sense of what the design "should look like" are not doing the job as they should.

It is desirable that students be expert in their roles before design begins, which in practice means that the engineers need more time to prepare than the architect or project manager. We have observed, however, that even if a participant does not fully understand all of the intricacies of their role, once play begins they are the expert.

3.2 Designing

We have traditionally started the exercise by having the architect layout a preliminary design for their team. This serves several purposes. First, it helps architects develop their aesthetic sense in a way that training cannot; more than the other roles, they need to learn by doing. Second, it gives the architects something to do while the engineers complete their more lengthy training. Finally, it is important to get something out quickly for the teams to work with, and experience shows that when all participate, initial designs are slow to materialize. Once they have an initial configuration in front of them, all can take part in designing, critiquing, recommend adjustments or even "let's start all over again."

Alternatively, designing could begin by presenting the team with an existing design, say of last year's model, or of a block house style which clearly won't meet the performance specifications. The most important point is to get the team going with a concept on the board, whatever its origins.

Once design is underway, the one rule for instructors is to not intervene or interfere. At their discretion, the instructor can answer questions, — a team might be charged a few zwigs or so for an outside consultant's input — but by and large, the teams should be left to fend for themselves. Take note of questions asked and cover them during training in the next round of the exercise. Our one exception to this rule has been to change the overhead factor if attention to cost seems inappropriately high or low.

Finally, the instructor should give a 10 minute warning to let teams know they need to finalize their design and calculate the performance measures requested in their handouts.

3.3 Presentation & Evaluation

At first glance, the teams' final designs are easy to evaluate and compare; each participant has the tools to analyze the design along their dimensions of responsibility, and the primers tell them that they will be asked to report hard performance measures at the end of the exercise. Even the architect can marshal numbers to discuss the mix and dispersion of colors, internal area, etc. Sometimes it works best to have a panel (perhaps made up of the tutors as judges) review the designs of different teams. But the reporting and comparison of specs should be regarded as only the first step in evaluation.

The first point to be raised at this juncture is that the evaluation of design is not a simple matter than can be reduced to numerical certainty. If a design is engineered to perfection but falls flat in the market place, is it a "good" design? What if it sells like hotcakes but is shoddily constructed? In the immediate context of the exercise, what if the clients really would have been happier with a bigger home and a cost overrun? Would they have willingly traded off slight thermal discomfort for aesthetic delight, or vice versa? What about the innate sense participants may have of which design simply looks better? There are many aspects of design quality that defy measurement.

The second point to be made is that, in this exercise anyway, the process of design is as important as the product, and that the two are closely linked. The purpose of Delta Design is not to learn how to best assemble triangles -- a skill in limited demand -- but to learn what transpires, and how to manage what transpires, when experts view a common goal through different lenses, and try to move towards it from different starting points. A key strength of the exercise is that the relationship between the quality of this process and the quality of the product is almost always strong and transparent. Teams that do the best job of mitigating conflicts and identifying complements between domains produce higher performance designs. If one is thinking of grading students' performance, we recommend that their work process be considered as important as the product of their efforts.

To surface these issues, we ask teams to present their own designs to the group, open the floor for questions and critique, and rapidly move the discussion from talking simply abut product to talking about process and the relationship between product and process. From there, the discussion usually takes on a life of its own and can be difficult to stop.

Delta Design THE DESIGN TASK

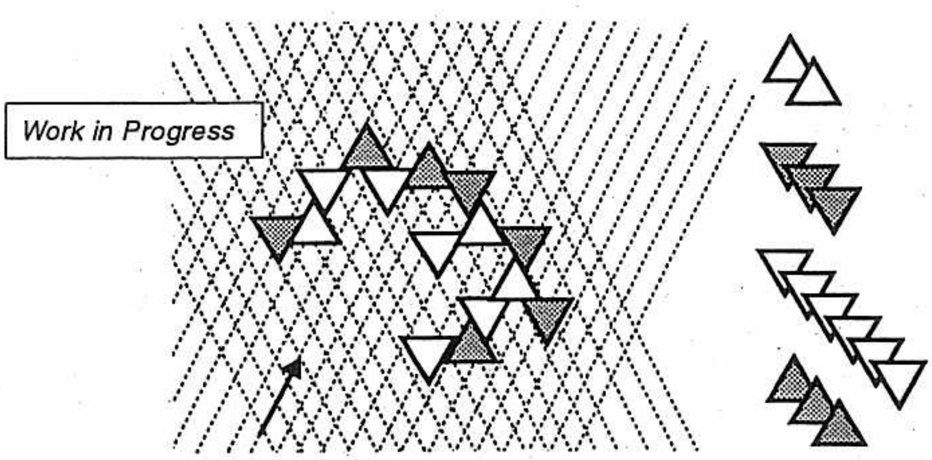
1.1 Introduction

Congratulations! You are now a member of an expert design team. Your collective task will be to design a new residence suitable for inhabitants of the imaginary Deltoid plane. These written materials, provided to help you prepare for this task, are organized in four sections.

The next section provides an overview of life on the Deltoid plane, DeltaP as it is known to the natives. The following section describes your team, and the final, your design task. A second handout, different for each team member, provides the specific information you will need to perform the role you have been assigned within your team. Each team member will contribute different expertise to the project, and each has different design responsibilities to fulfill. All must work together for your team to create a first-rate design.

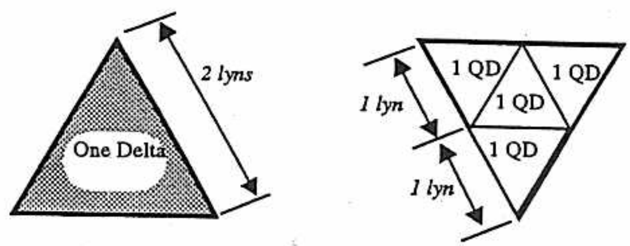
1.2 Life on DeltaP

Life on DeltaP, residential and otherwise, is quite different from what you have grown accustomed to here on Earth. First off, DeltaP is a plane, not a planet, so your team will be designing in two-dimensional rather than three-dimensional space. If your design "meets spec" and is considered attractive and functional by your Deltan clients, one view on a single sheet of paper will convey to those responsible for constructing it all the information they need to do so.



The view on this single sheet may not be quite what you expect, however, because in addition to lacking a z axis, Deltoid space has unfamiliar relations between the x and y axes as well. What we think of as "perpendicular" is hopelessly skewed to a Deltan, and vice-versa. In our units, a right angle on DeltaP measures 60° or $\pi/3$ radians. Thus all sides of an equilateral triangle form lines considered perpendicular to all others. If there were such a thing as a "circle" on DeltaP, it would be composed of only $4\pi/3$ radians.

But there is no such thing as a "circle" on DeltaP, nor even the concept of continuity embodied therein. In this flat though angular world, residents construct their artifacts strictly with discrete triangular forms. Of these, the equilateral triangle -- with its three perpendicular sides (!)-- is considered the most pleasing. Accordingly, your team will design the residence by assembling into a



1 QD = *1 quarter delta*

cluster the most prized building materials on DeltaP, equilateral triangular components called "deltas." Deltas come in red and blue versions and always measure *2 lyns* per side. Four "quarter-deltas", *QDs*, triangular units of area measure with sides of *1 lyn*, fit within a delta.

Lyns? QDs? Not surprisingly, Deltan systems of measurement are as unfamiliar as that for spatial coordinates. Table 1 summarizes the measurement schemes on DeltaP that you will need to know to carry out your design task.

All of DeltaP's units of measure share the divisibility and extensibility conventions of the metric

TABLE 1. **Measurements on DeltaP**

Measurement	Unit of Measurement	Symbol
Time	Wex	wx
Distance	Lyn	ln
Area	Quarter-Delta	qd
Heat	Deltan Thermal Unit	DTU
Temperature	Degrees Nin	°Nn
Force	Din	Dn
Moment	Lyn-Din	LD
Currency	Zwig	!

system; in the measure of time, for example, there are both microwex (μwx) and megawex (Mwx). In relation to the attention-and life-spans of Deltans, these units are roughly equivalent to seconds and years, respectively, here on Earth.

As building components, deltas have functional and aesthetic characteristics that are more complex than their simple form and even dimensions would suggest. Especially when assembled into a cluster, as you will be doing, they behave in interesting ways. Deltas conduct heat among themselves, radiate heat to outer space, melt if too hot, and grow if too cool. Red deltas produce heat. All deltas are subject to DeltaP's two-dimensional gravity (which is itself subject to axial shifts during DeltaP's not-infrequent gravity waves). Three different kinds of cement are needed to join them together, and joint alignment with respect to gravity affects ease of production as well as structural integrity. Different colors and different quantities of deltas cost different amounts of money per delta, and can be assembled in clusters that are either exceedingly ugly or very attractive to the Deltans. Your task will be to create a design that meets prescribed goals for all of these characteristics.

1.3 Design Team Roles & Responsibilities

Your design team is organized such that each of you will be responsible for a subset of the design goals. One of you will be PROJECT MANAGER. Your main concerns will be with cost and schedule, the interpretation and reconciliation of performance specifications, and negotiations with the contractor and client. You want to keep costs and time-to-build at a minimum, but not at the expense of quality. When your team submits its final design, the project manager must report the estimated cost (in zwigs) and the time (in wex) that it will take to build.

Another of you will be the STRUCTURAL ENGINEER. Your main concern will be to see that the design "holds together" as a physical structure under prescribed loading conditions. You must see to it that the two points at which your structure is tied to ground are appropriately chosen and that continuity of the structure is maintained. When your team submits its final design, the structural engineer must attest to its integrity by identifying the strongest and weakest joints, and estimating the average load on all joints expressed as a percentage of the failure load.

Another of you will be the THERMAL ENGINEER. You will want to insure that the design meets the "comfort-zone" conditions specified in terms of an average temperature. You must also ensure that the temperature of all individual deltas stays within certain bounds. When your team submits its final design, the thermal engineer must estimate internal temperature and identify the hottest and coldest deltas.

Finally, one of you will be the ARCHITECT. Your concern is with both the form of the design in and of itself and how it stands in its setting. You must see to it that the interior of the residence takes an appropriate form and that egress is convenient. You should also develop a design with character. When your team submits its final design, the architect should be prepared to present a sketch and discuss generally how and why the Deltans will find the residence attractive and functional. The architect will also be asked to estimate a few more quantitative measures of architectural performance.

The following section describes the specifications that your design must meet to be accepted by your clients on DeltaP. Familiarize yourself with these specifications. Then, for schooling in your specialty, turn to the separate primer you have received that discusses the science and technology of your domain. The primer contains the knowledge and heuristics you will need to estimate the design parameters for which you are responsible. If you have questions that it does not answer, do not hesitate to ask. You should be expert in your role before your team begins the design phase.

1.4 The Design Task

Your Deltan clients have cleared the space shown on the site map and come to your team with their need for the design of a new residential cluster. The cluster itself must meet the following specifications.

The client wants the cluster to provide a minimum interior area of 100 QDs (Each diamond on your girded site map defines an area of two QDs). The shape of this space, which can of course exceed the minimum, is a matter of design. The client has expressed enthusiasm for the newer mode of segmenting interior space, a mode that breaks with the two-equal-zone tradition and values the suggested privacy of nooks and crannies. Still the space must be connected, i.e. no interior walls can cut the space into completely separate spaces. There must be one and only one entrance/exit.

The client is known to be color sensitive blue; too much blue brings on the blues, so to speak. No more than 60% blue ought to be allowed; certainly blue deltas are not to exceed 70% of the cluster.

The residence, as all clusters, must be anchored at two points and two points only. There is a limit to the amount of force each anchor can support, as well as to the amount of internal moment each joint can withstand. Exceeding either limit would cause catastrophic failure and send the unwary residents tumbling into the void. The cluster should be designed for a life of thirty megawex. Gravity waves, rare but always possible, should be considered.

The average interior temperature must be kept within the Deltan comfort zone, which lies between 55 and 65 °Nin. The temperature of the elements themselves must be kept above the growth point of 20 °Nn and below the melt-down point of 85 °Nn. Delta temperatures outside of this range will result in catastrophic structural failure with little more warning than excessive load.

All of this -- design, fabrication and construction -- must be done under a fixed budget and within a given time period. At your team meeting you are to develop a conceptual design that meets or exceeds all design goals. When each team submits their design, individual members will be asked to report design performance on parameters for which they are responsible.

TABLE 2. **Summary of Design Specifications**

Functional Internal Area	100 qd
Maximum Cool Deltas (% Total)	60-70%
Average Internal Temperature Range	55-65 °Nn
Individual Delta Temperature Range	20-85 °Nn
Maximum Load at Anchor Points	20 Dn
Maximum Internal Moment	40 LD
Overhead Factor -K	(varies)
Total Budget	! 1400.00