Delta Design: Seeing/Seeing as

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> "....On ne trouvera point de Figures dans cet Ouvrage. Les methodes que j'y expose ne demandent ni constructions, ni raisonnements geometriques ou mechaniques, mais seulement des operations algebriques, assujetties a une marche reguliere et uniforme. Ceux qui aiment l'Analyse, verront avec plaisir la Mechanique en devenir une nouvelle branche, et me savront gre d'en avoir etendu ainsi le domaine." [Extrait des registres de l'Academie royale des Sciences, du vingth-sept Fevier mil sept cent quatre-vingt-huit. *Mechanique Analytique* par J.L. Lagrange]

1.0 Introduction

Lagrange had no place for figures in his classic treatise on analytical mechanics. While the reader might complain that his treatment would have been clearer if he had, Lagrange was out to make a point: His analytical mechanics, being based on a scalar, energy principle - whether employed to determine the tension in a cable, the motion of a ball rolling down an inclined plane, the trajectory of a projectile - had no need for figures in the form of 'free-body' diagrams, geometric constructions, or vector diagrams in order to produce useful results.

Lagrange's book is not a designer's handbook. But the principles and methods he espouses are very much a part of designing, at least in the hands of engineers responsible for the design of cables, mechanisms, robotic manipulators, trajectories of projectiles - a variety of mechanical mechanisms and systems. For example:

Picture an earth orbiting satellite drawing its power from two solar panels attached at the ends of two arms extended straight out from its body. Each arm, like our own, is built of two segments articulated at an elbow - a joint which allows the rotation of one segment relative to the other. It is designed this way so that during the launching of the satellite atop a boost vehicle, the arms can be folded up and the solar panels safely stowed against the body and fit under a nose cone. When the satellite is injected into orbit, a pyrotechnic device fires on command which releases a restraint on a small, compact, coiled spring at the joint where the upper arm meets the body; the spring drives a wheel which pulls taught a cable which in turn drives a second grooved wheel at the elbow fixed to the outer segment of the arm and so rotates the latter relative to the upper arm until both are in line at which point a latch engages and the assembly, with solar panel appropriately extended, is locked in place.

The engineer responsible for the design of this mechanical subsystem had to define, for those who would build it, the lengths of the two arm segments, their section properties, the specifications of the coil spring, of a viscous damper, the diameters of the grooved wheels, as well the details of fasteners, joints, materials, electrical cable routing and the like. The engineer used Lagrange's method, constructing a model of the dynamic behavior of the arm in the form of a non-linear, time-varying, second-order differential equation which defined the configuration of the system as it unfurled. From its solution several times over, he proposed and justified a particular set of the fore mentioned mechanical properties.

Unlike Lagrange, the engineer *did* rely upon figures in his working up of the model and in the presentation of his design. His derivation of the differential equation needed a sketch which enabled the construction of an explicit relationship for the relative position of the outer segment relative to the upper arm segment - describing the configuration of the articulated pieces of the system as a function of the angular position of the upper arm alone. This was essential to writing out expressions for the kinetic energy of the segments, and the solar panel, as a function of the angular position (and velocity) of the upper arm alone. The kinetic energy, together with the potential energy of the coiled spring, are the main variables entering into "Lagrange's equations".

Before committing to the particular arm lengths, wheel sizes, types of spring and damper, a physical model - a prototype of sorts - was built and tested. Only after this was shown to work was the design frozen.

Here then is design representation in engineering and in a variety of modes, i.e.,

The prototype is a design representation. It is constructed to test ideas and specifications; it is a conjecture, although of a admittedly "hard" and relatively expensive sort. But it is sketchy in that it is not the real thing; the solar panels were simulated using distributed masses, the electrical cabling was not included, and the gravity-less nature of earth orbit could only be approximated by an innovative suspension system.

The sketches, of course, are design representations. Their appearance, content, and formality depend upon the audience. The engineer, when working alone in what I call an 'object world', is his own audience. His sketch performance, like a speech act, is a transient event - he comes back in a year and he may no longer be able to read what he drew without considerable lateral searching and reconstruction of his Lagrangian analysis. The figures in his memo, documenting the proposed design, have a wider audience and a greater degree of permanence. In both cases these images only have meaning when read within the Lagrangian paradigm.

The non-linear, time-varying, second-order differential equation is a design representation. It goes with the figures and the prototype. Only a reader schooled in the object world of the mechanical engineer can appreciated and fathom its meaning and relevance to the design of the solar panel deployment scheme. Certain parameters which appear can be easily varied, the model "run", and the change in performance determined. Will the dynamic stress in the arm at the root at latching exceed acceptable levels? Should we add more damping? If we do, are we sure the latch will engage? What energy ought to be initially stored in the spring? The engineer "reads" thus his way into and out of the differential equation.

Finally, my narrative, beginning with "picture an earth orbiting satellite...", is a design representation. It too, like Lagrange's, would profit from a figure. But I want to make a point: design representations by engineers take a variety of forms, even within one discipline. Story making with a heavy use of figurative language, of metaphor dead and alive, is just as much a creative act of design representation as is the sketching of a spatial configuration, the construction and manipulation of a differential equation or the crafting of a prototype.

There are differences and variety of other sorts - what we might consider different dimensions of engineering design representations. We can talk about the private or public nature of a representation; about the formality or informality of a representation; about its analytical intensity or particular realism. These stand above differences across disciplines - disciplines with different paradigmatic bases, different conventions, different technical foci and interests. And these differences across disciplines are important, not just of academic interest, because engineering design requires their mix.

I am not going to cover all of this territory - all the modes of representation used by all the different kinds of participants in designing. Rather, using a design negotiation exercise I have developed as a reference, I offer some examples of differences - differences in nature and purpose of representations of selected engineering disciplines, of participants working within different object worlds. Through them I want to illustrate how each discipline has available a variety of modes of representation to think and act through design possibilities, modes which range from the abstract, even symbolic, rich in analytic significance to the concrete where details of properties and positioning of hardware are important. I want to show how, to better understand what's going on when engineers make and use these various representations, we must be ready to probe beneath the surface appearances and explore the different ways objects are understood, expressed, and manipulated. In engineering design, the object of design is "seen" (read) by different participants in different ways according to their individual responsibilities and technical interests.

2.0 Engineering Design/Delta Design - A Social Process

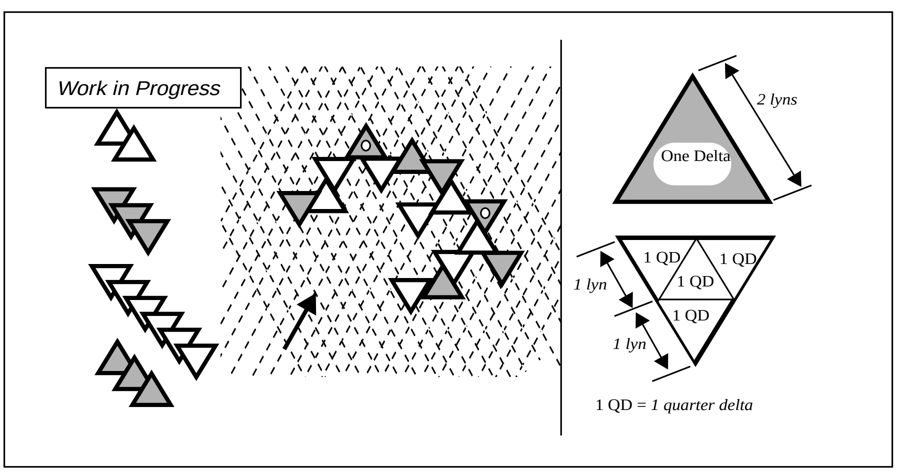
In *Designing Engineers* (MIT Press, 1994), I describe the engineering design process as a social process. In each of the three firms I studied - one designing a photovoltaic module, a second an x-ray inspection machine, the third, a photprint maker - designing was done by a group of individuals, working as a team.

Although the strength of the bonds, the degree of "teaming" varied from firm to firm, in each case, every individual worked, at least part of the time, within what I have label his or her own "object world". For example, the group at Solaray, engaged in the design and development of a relatively large photovoltaic module, included a mechanical engineer responsible for the design of the frame, the protective layers of backing, the sizing of the cover glass, and assembly of the product; several electrical engineers were responsible for the design of the series/parallel circuitry of the photovoltaic cells, of the number and placement of diodes, and of the choice of electrical hardware including junctions and cabling; an individual from cell production was responsible for the characterization of the individual cell's performance and how statistical variations in performance would effect the output of the module as a whole; a marketing person with an engineering background was concerned that the module characteristics matched the needs of the entire system, so that system configurations could respond to market opportunities; another electrical engineer was responsible for the design of system controls, in particular, the choice and sizing of battery capacity for energy storage (or DC/AC inverter technology if the system was connected to the electric utility grid). All of these people had some say about the design of the new, large photovoltaic module. Each saw the design differently.

The differences in readings of the photovoltaic module spring from the individual's technical learning and experience. Each individual projects out into the design process her or his own reading of the object. It's like a classical theory of vision that had rays emanating from the eye out onto the world, rays which reflect and return to the seer signaling the presence and nature of the object. To extend the analogy, different individuals emit rays of a different character which are reflected back differently by the object.

The *Delta Design* game is meant as an abstraction of the engineering design process which brings explicitly to the fore this vision of designing as a social process of negotiation among participants who see, represent, analyze, and talk about the object, or subject, of design differently. It engages students, within a three or four hour time period, in an engineering design task that requires the collective efforts of four participants - an architect, a project manager, a structural engineer, and a thermal engineer. It begins, in a document common to all roles, with:

> 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....



Life on DeltaP, residential and otherwise, is described as different. DeltaP is a plane, not a planet, so the team designs in two-dimensional rather than three-dimensional space. Deltoid space has unfamiliar relations between the x and y axes as well. What we think of as “perpendicular” is skewed to a Deltan. In our units, a right angle on DeltaP measures 60^{o}. In this flat though angular world, residents construct their artifacts strictly with discrete triangular forms. Of these, the equilateral triangle, a “delta” -- with its three perpendicular sides (!)-- is considered the most pleasing. The deltas come in red and blue versions and always measure *2 lyns* per side. Four “quarter-deltas”, *QD*s, triangular units of area measure with sides of *1 lyn*, fit within a delta.

As building components, deltas have functional and aesthetic characteristics that are more complex than their simple form would suggest. When assembled into a cluster, Deltas conduct heat among themselves at a rate which depends upon their overlap and the difference in their temperatures - the latter measured in “degrees Nn”.   They radiate heat to outer space, melt if too hot, and grow if too cool but only the red deltas produce heat. The average interior temperature must be kept within the Deltan comfort zone, which lies between 55 and 65 ^{o}Nn. The temperature of each individual delta must be kept above the growth point of 20 ^{o}Nn and below the melt-down point of 85 ^{o}Nn. Delta temperatures outside of this range will result in catastrophic structural failure with little more warning than excessive load.

All deltas are subject to DeltaP’s two-dimensional gravitational force, measured in “Dyns” - each delta experiencing 1 Dyn. 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 - measured in “lyn-dyns” - 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 lifetime of thirty megawex - a wex is the unit of time. Gravity waves, which shift the gravitational force a full right angle, are rare but always possible; the effect of theses too should be considered.

Three different kinds of cement, at three different costs, are needed to join deltas together - depending upon their relative colors, - 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 - the red deltas cost !8, that’s 8 “zwigs” each. Blue deltas cost !10 apiece. (There is a price break if you buy more than 20 reds and more than 16 blues). All of this -- design, fabrication and construction -- must be done under a fixed budget of !1400 and within a given time period.

The deltas can be assembled in clusters that are either exceedingly ugly or very attractive to the Deltans. The client wants the cluster to provide a minimum interior area of 100 QDs (Each diamond on the 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..

Summary of Design Specifications

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

The DeltaP has some bizarre features - its dimensionality, its non-orthogonal geometry, its naming of physical units, the needs of its inhabitants, the physical behavior of its elements, the sciences on DeltaP. It is made different from our own world for several reasons. It is two-dimensional so that the players can more easily link-up what they are doing, seeing, and manipulating “on paper” with the real world - in this case the real, two-dimensional, DeltaP world. (That there is no “real DeltaP world” does not seem to bother the players one bit - they take on their respective roles, develop and engage them as if there indeed was a real world out there somewhere - just as our engineering students engage the abstract exercises we present them with as if there were a real Earth world out there).

More importantly, these bizarre features tend to negate and render unimportant any differences in skills and experiences participants bring to the design task. They level the playing field so to speak. And because participants are not accustomed to working with a non-orthogonal coordinate system, the parameters and properties of DeltaP, or the new instrumentalities of their assigned disciplines, they must be educated in their roles. As each player has in-depth access only to his or her own discipline, each player becomes an “expert” - their respective object worlds remain isolated one from the other. The hour or so before the teams form is used to prepare, to educate participants.

As to the responsibilities of the participants: The Project Manager’s main concerns are with cost and schedule, the interpretation and reconciliation of performance specifications... costs and time-to-build are to be minimized, but not at the expense of quality. The project manager must be able to identify a module and its boundaries.

The Structural Engineer. needs to see that the design “holds together” as a physical structure under prescribed loading conditions. The two points at which the structure is tied to ground must be appropriately chosen and continuity of the structure must be maintained. He or she must learn to estimate the torque about any point in the structure due to the gravitational force acting on each delta. Because perpendicular distance to the line of action of a force is defined differently than is the rule in our world, he or she must learn to do so for the Delta World. In estimating the support loads, use can be made of symmetry, but symmetry looks different enough from what one is normally accustomed to that learning again is required.

The Thermal Engineer must insure that the design meets the “comfort-zone” conditions specified in terms of an average temperature and that the temperature of all individual deltas stays within certain bounds. The thermal engineer must learn to identify inward and outward pointing nodes and to estimate the radiating length associated with each outward pointing node.

Finally, the Architect is concerned with both the form of the design in and of itself and how it stands in its setting. The interior of the residence must take an appropriate form and egress is to be convenient. The product should be a design with character. The architect must be able to figure the enclosed area in terms of “quarter-deltas”.

These are not terribly complex tasks once one is tutored in the methods contained in each of the four role instructions. (Think of these as the textbooks for a very short course). But the task is hard enough, the Delta World science different enough, to establish distinct object-worlds in accord with my representation of design process where different individuals with different responsibilities and interests “see”, read the design differently. This ability to read is again the aim of the training in their respective roles.

For example, the structural engineer, in estimating the support loads and the internal moment at any interface, will begin to see the assembly as a simply supported beam subject to a load varying along its length. Picture a further abstraction of the one figure in this paper, (labeled ‘Work In Progress’). Envision a beam running diagonally at 60 degrees to the horizontal from the upper left to lower right, “perpendicular” to the direction of the gravity vector. Now show the distributed and spatially varying load on the beam by a series of vectors of varying length, all with their arrow heads resting on the beam and pointing in the same direction as the gravity vector. The whole assembly of loads and beam is supported at two points located along the span at the same relative distance as the small circles shown in the original figure. Using this sketch showing vector forces and spatial configuration, the structural engineer can determine the reaction forces at the two support points, forces limited by the design specifications.

A further application of the principles of static equilibrium to a sequence of still more abstract “free body diagrams” gives estimates of moments internal to the beam; the latter must also be less than a certain limit lest the structure break apart when built.

The thermal engineer, viewing the same original “Work in Progress” drawing will see something different. Picture now another abstraction. This time spatial location doesn’t matter but the connectivity of the elements, their color, and their orientation with respect to outer space does. Envision a series of points (small circles or probably equilateral triangles) running across the paper from left to right each representing a delta element. A single short arrow connects each point on the left to the adjacent one to the right, indicating the assumed direction of positive heat flow. Other short arrows, now with a wiggly tail, appear in the figure: those pointing into a element from below indicate the element is a red delta, a heat source. The arrow symbolizes the rate of heat generation of the element, flowing into the system. Those pointing up, out of an element, indicate the element is radiating heat to outer space, out of the system. The length of these arrows are proportional to the radiating length of the element’s outward pointing node.

This picture is only a halfway point; a further abstraction leads to a system of coupled, first order, linear differential equations for the time-varying temperature of each element. The steady state solution is of particular interest - it fixes the cluster average temperature which must lie within certain limits.

While both engineers start from the same image, the same object, the representations they construct for their purposes are quite different. In the world of the structural engineer, the geometry, the positioning of the load vectors in space, the distance between the supports, is retained from the common image on the left. Within the world of the thermal engineer, these features matter little; now the connectivity of the elements is important, so too their color. While both object world representations include arrows, the straight ones in the structural engineer’s representation have their lengths proportional to the force over a discrete section of the beam; the lengths of the wiggly ones in the thermal engineer’s world are proportional to the radiating length associated with each outward pointing node.

The structural engineer’s representation leads to further images, free-body diagrams,, then the application of the principles of static equilibrium to produce equations which determine the torques at all internal junctions. The thermal engineer’s representation leads directly to a system of linear, ordinary differential equations for the time varying temperature of each delta.

Picking up on the sightseeing metaphor of the introduction, think of each participant having a special pair of glasses. The structural engineer’s pair is different from the thermal engineer’s, is different from the project manager’s, is different from the architect’s pair. Each pair of glasses filters out all information irrelevant to the role of the wearer; it only allows through the properties, abstract entities, the relationships among these latter, which have meaning to the wearer. The thermal engineer sees the heat radiating out from certain nodes, sees the red deltas as distinguished from the blue; but the gravitational force on each delta is not seen, nor is the shape of the layout important; the structural engineer sees neither blue nor red but simply the equilateral triangle; spatial configuration is important, the support points are emphasized, and the gravitational vector looms large. Etc.

Here then is an example of participants in design, responsible for different features or functioning of the product, looking at the same thing and seeing something different. It’s the difference between “seeing” and “seeing as”. Different participants, working within different object worlds, *see* the same object of design yet *see* it *as* something different.

3.0 Summing Up

Engineering design representations take a variety of forms. Different disciplines, different forms. Only examples from two domains - those of a structural engineer, a thermal engineer - have been displayed here and these only within the context of an abstract exercise. But it is not difficult to imagine the forms employed by others - the block diagrams of a controls engineer, the coding of a machine language programmer; the Pert charts of a project manager; the circuit diagrams of a traditional electrical engineer; the matrix representation of a Markov process of a logistics engineering, the wind tunnel prototype of a vehicle fashioned by an aeronautical engineer - and the stories these various people might tell in the course of design. Modes of representation vary over disciplines, from object world to object world. A sketch in one discipline can be of spatial organization and location of things; in another, a representation of heat flows, sources and sinks; in yet another a network of electrical devices; in still another, a thermodynamic cycle; all of which is a matter of conventions of disciplines intimately tied up with their paradigmatic conceptual and instrumental apparatus.

Within each discipline there is variety again; a system of equations is as much a design representation as is a sketch or a physical prototype which, like a sketch, has much that is missing in its representation of features.

So design representations in engineering show varieties of forms. To fully understand their production and use, one must see them in context. One must *see* them *as* terms of design discourse, both within object worlds where the discourse is often a monologue - an individual deriving, symbolizing, sketching, saying, building and testing by him or herself alone - and within the more social and collective enterprise of negotiation across object worlds. This paper has focused on object world representations. As such, as terms of an instrumental, particular engineering discipline, the meaning of a representation, of whatever form, is only grasp in relation to the concepts and principles, codified and tacit knowledge, norms and beliefs of the discipline. When we study design representation in engineering, we want to make sure we move beyond “seeing” the elegance of a system of differential equations, the creativity expressed in a finely machined prototype, the artistry of the sketch, or the eloquent use of metaphor in a narrative of function, to grapple with the underlying forms, conventions, and language of alien object worlds. Only then might we better understand, not only the difficulties of communicating across object worlds, but the ways in which digital technology might be fashioned to help practitioners “see as” better.

There are times during the Delta Design exercise when an outside observer will see all four participants pointing at the cluster, motioning as if they were counting. What one doesn’t see is that they are all counting and figuring something different.

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