scripting concrete

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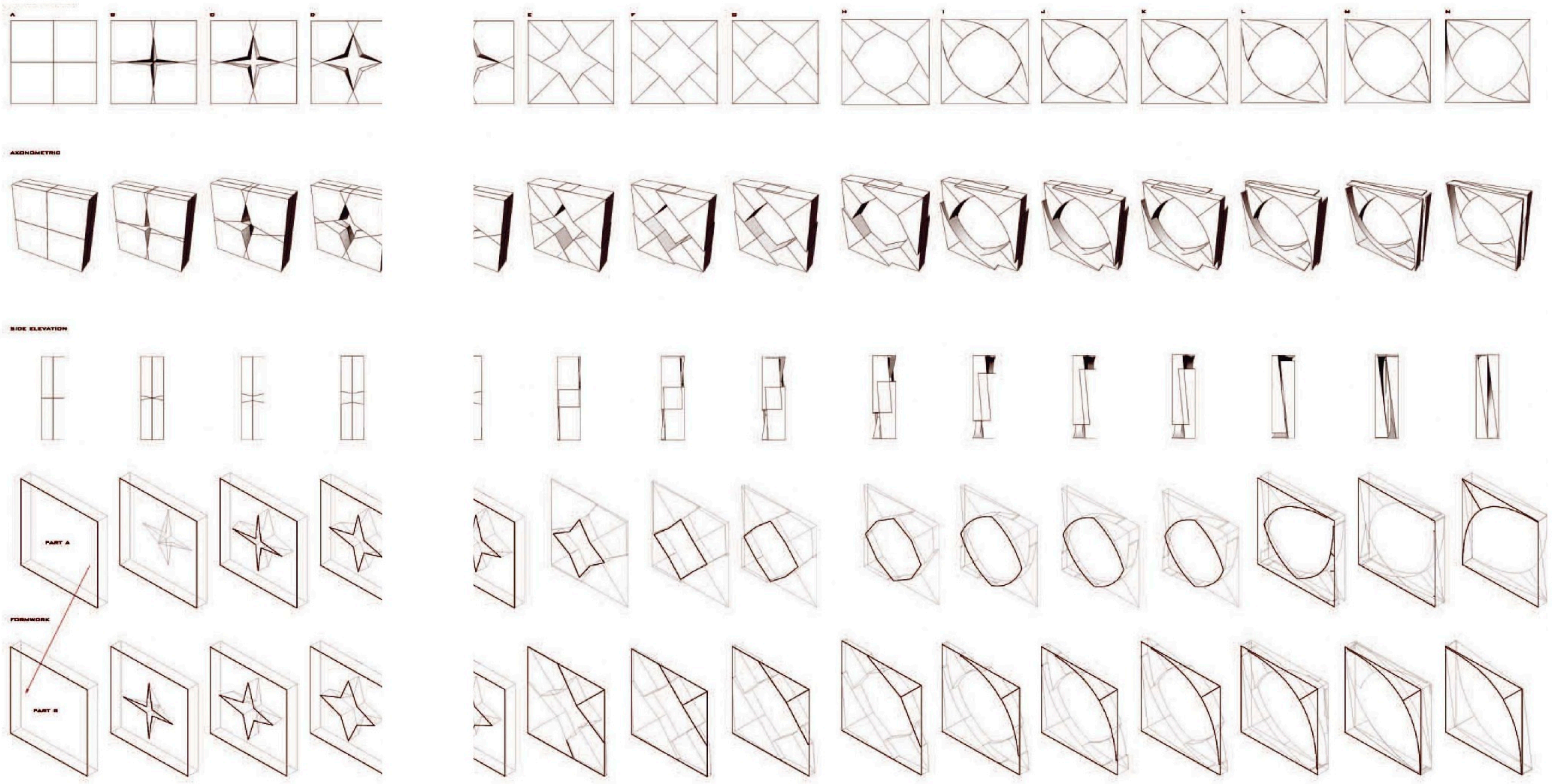
1. Introduction

Exploration of problems of geometry and form vis-à-vis specific means and methods of assembly and construction has always been a central question in architectural pedagogy and practice. Not all types of geometries are possible within given construction domains and not all construction techniques are suitable to solve given formal problems. An iterative loop is clearly suggested at the outset of the problem and novelty is warranted by the designer's reflective understanding of the interplay between both domains of composition and construction. This paper discusses the design of an architectural pedagogy that is based on this reflection-in-action ethos and gives a brief account of its implementation in an advanced graduate architecture studio curriculum.

Among many and different kinds of ways that an architectural pedagogy can be designed to foreground specific relations between composition and construction, computation promises a most significant role: computer-controlled design algorithms visualize designs that would be difficult or even impossible to be thought and described otherwise; similarly, computer-controlled fabrication machinery produces designs that would be very difficult to or even im-



1_**Sample of the cast modules and the prototypes developed (Lorraine Ong).**

possible to be produced otherwise. The specific methodology described here has been particularly choreographed around issues pertaining to the design and fabrication of concrete structures. If generally, construction methods are rooted in problems of aggregation, of assembly, and of joinery using conventional 'units' of construction, the foundational difference in the construction of concrete is its indexical relationship to those very processes: concrete imprints the marks of formwork, it registers it, it mirrors it, and it tattoos it; its raw liquid state is defying any immediate additive assembly process. This dialectical relationship between the figuration of concrete form and the corollary configuration of elements that create formwork define the medium at its core. Alternatively, if concrete has seen a range of expressions throughout history, it is due to the varied techniques for formworks that have produced the mold for which these casts have become known. These techniques are examined here further as a way of understanding the nature of concrete construction- and moreover the nature of casting as a broader tectonic and computational medium.

A series of design studies is described here are presented as systematic studies exploring the nature of casting including aspects of its representation, its parametric definition, its algorithmic definition, and its prototyping. An underlying motivation for the whole project is based in our conviction that if conventional buildings thrive on mass production, recent possibilities of mass customization to adapt concrete to particular circumstances, may very well emerge from computational, technological, structural, programmatic, and geographic contingencies. The design studies -and the curriculum itself of the advanced architectural design studio- can differ dramatically to foreground diverse aspects of these contingencies; here a brief account will be given to the overall structure of the proposed studies and the emphasis will be given in the systematic exploration of the design worlds linking underlying configuration (what is topologically possible in a given design space) and the casting techniques and the associated algorithms that shape / figure these configurations.

2. Form/formwork

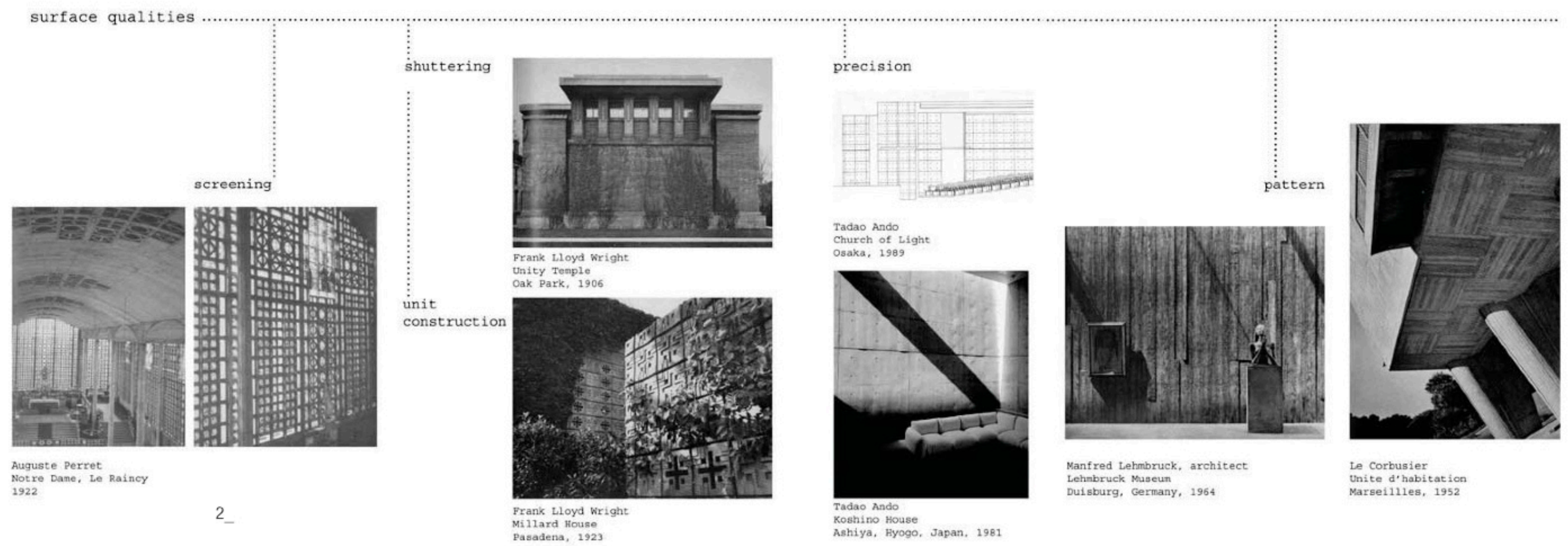
The studio pedagogy is structured around a series of four studies that are all meant to explore different aspects of the nature of casting; aspects of its representation, its parametric definition, its algorithmic definition, and its prototyping. The first exercise suggests a brief look at the history and logic of casting: the various techniques that history has practiced including cast-in-place, fabric-formed, pre-cast, as well as more recent digitally oriented practices. The goal here to examine constructively how two-dimensional surfaces are formed to define frameworks for three-dimensional molds: that is, how two-dimensional surfaces of, say, wood, steel, fiberglass, etc., have to be manipulated in order to render orthogonal precision, curvature, folds, ruled surfaces, and complex geometries. A sample of such explorations is given in Figure 2.

The second study implements some of the lessons encountered in the first study towards the design of a bounded surface unfolded in three dimensions featuring at least one or more holes – that is to say, a closed surface of topological genus n, for n>1. The feature of the opening is a significant part of the design problem to guarantee an encounter with the geometrical complexities of surface boundary, continuity, and closure, and to evoke apt functional vocabularies routinely employed in architectural settings as windows, doors, staircases, chimneys, gutters and so forth. The outcome of the computation is the specification of the formwork; not the form to foreground reciprocal relation of figure/ground, solid/open and similar design problems that such reversals suggest. A sample of such explorations is shown in Figure 3.

The third study synthesizes the results of the first two studies to create a cast module of x.y.z modules, typically 1 x 2 x 4 meters, within which multiple architectural contingencies can be embedded. The module can be conceived as a programmable zone that can define the liner of a building. As such, its architectural duties are to establish some relationship between structure and skin, to calibrate the passage and quality of light, and most importantly for this exercise to establish a specific relationship to the body. Furthermore, this threshold between the inside and outside of the building is considered as an opportunity to investigate the relationship between architecture and furniture, using the body as the ergonomic measure of the cast. As a hand fits in a glove, the body is suggested to be molded into the building liner, not only for establishing a scale for the exercise, but as an alibi to negotiate the relationship between complex and simple geometries.

The fourth study requires a generous reflection of the formwork studies produced so far and their literal recasting in algorithmic terms. More specifically, the study requires an algorithmic exploration of the forms and the casts -and the modules they produce and their combinations in growth structures- so that the initial studies can provide the input for general systems that explore topologically and figuratively formal variations. The goal here is to script the forms and the casts, and express them in terms of functions, variables, statements, expressions, complex data types and arrays. The background of this work is the systematic encounter with the mathematics of growth; the foreground of this work is the generalization of what has been already produced. It is suggested here that this encoding of form and formwork challenges conventional ways of thinking about design routinely produced in studio and brings to the foreground underlying assumptions and conventions used in design. In essence, the task here is the parametric description of the designs dealt so far. It is expected that the attempt to describe their forms in this manner would not only describe a whole class of designs that share similar characteristics with the ones described or produced so far, but that they would also suggest possibilities that would have been entirely off the discourse unless this parametric definition had been attempted. Various methods are suggested to foreground this parametric definition; most of them coalesce around the notion of a simultaneous exhibition of all spatial variants on a single surface simulating a gradual growth. A sample of such explorations is shown in Figures 4(a) - 4(c).

Among all possible construals of the parametric definition of the cast - some may be foregrounded more than others. In the context of the pedagogy of this set of design studies, the granularity and scale of the module, the number of iterations to show the gradual morphing of



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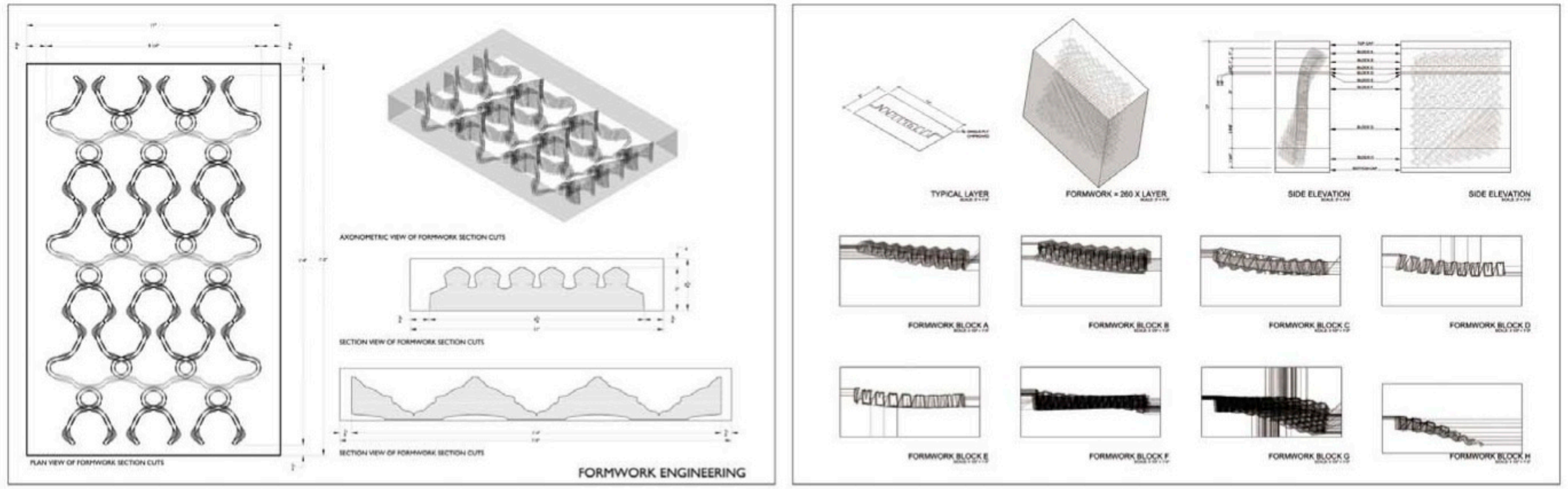

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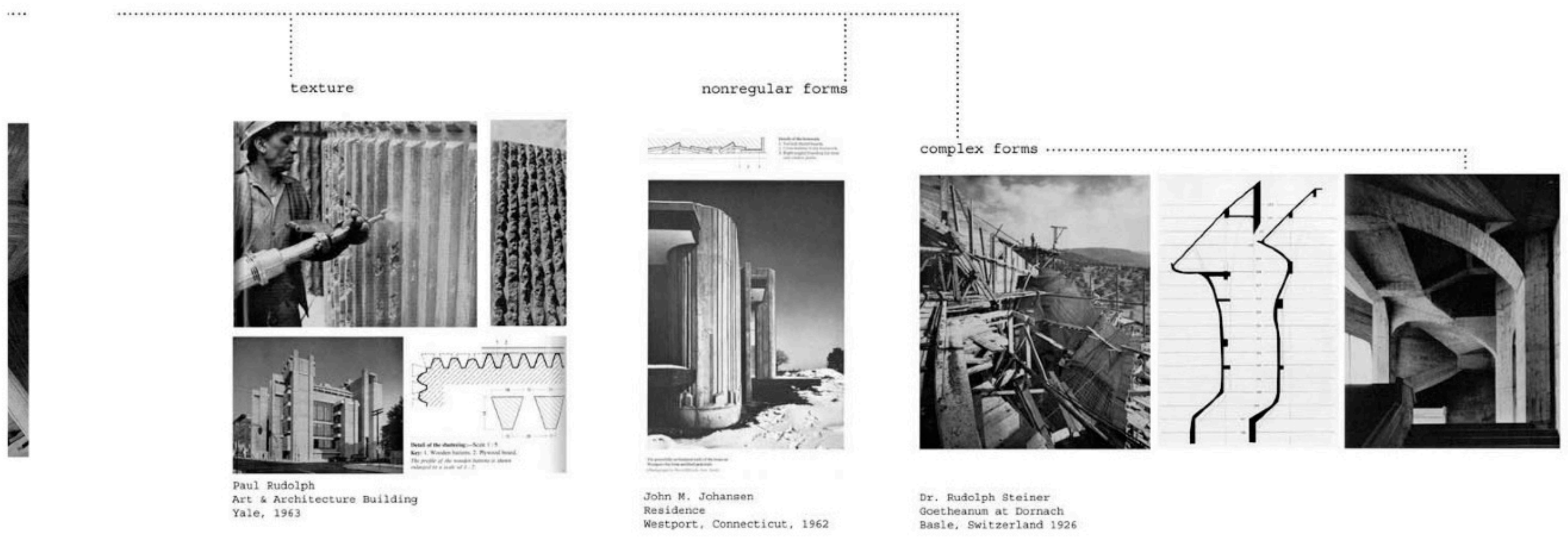
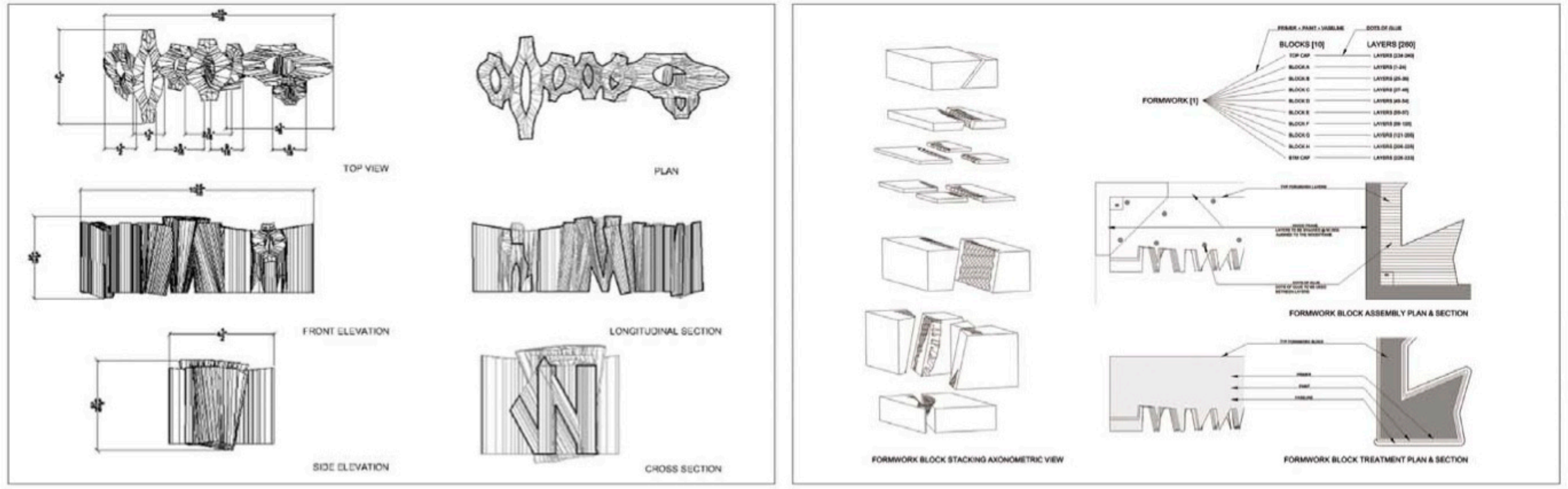
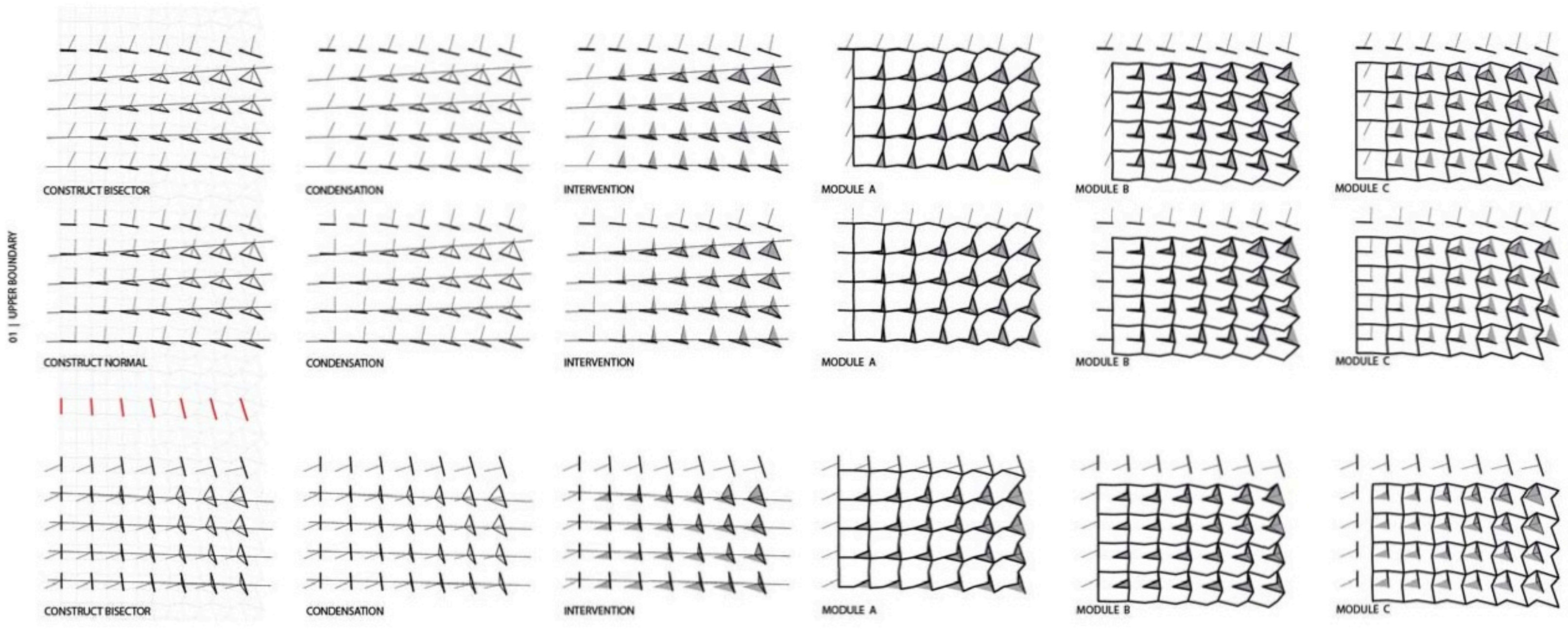
2_ **Samples from the joint studio research on casting concrete (Richard Aeck, Erin Lindley, James Okelley, Lorraine Ong, Wendi Rahm).**

3_ **Samples of the drawing specifications of the formwork of the surfaces (Richard Aeck, Erin Lindley, James Okelley, Lorraine Ong, Wendi Rahm).**







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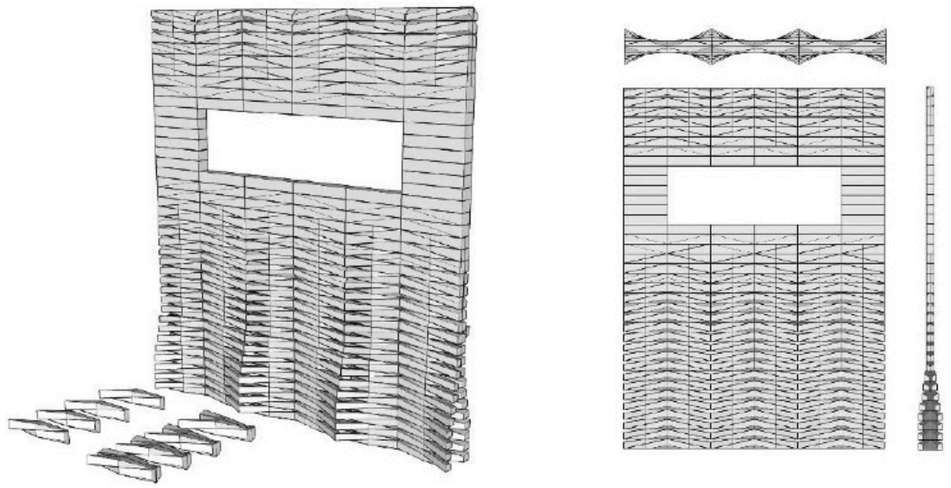
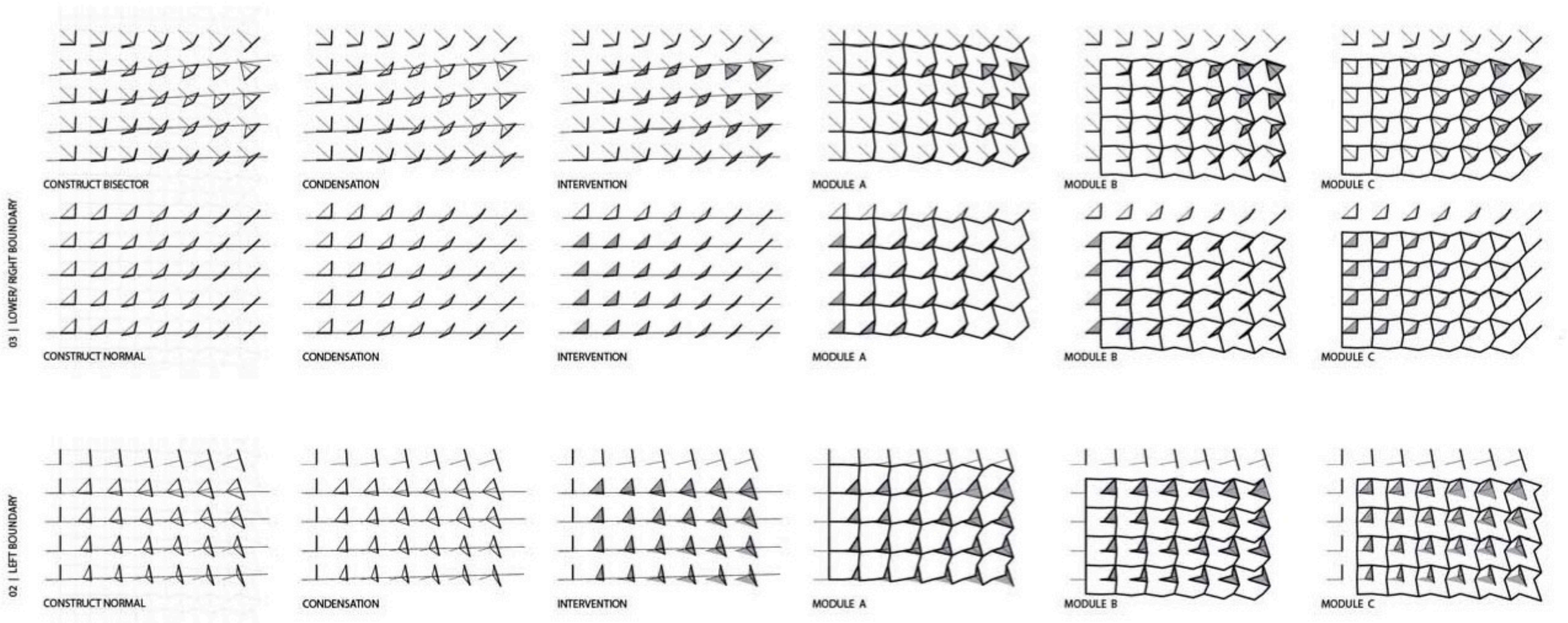
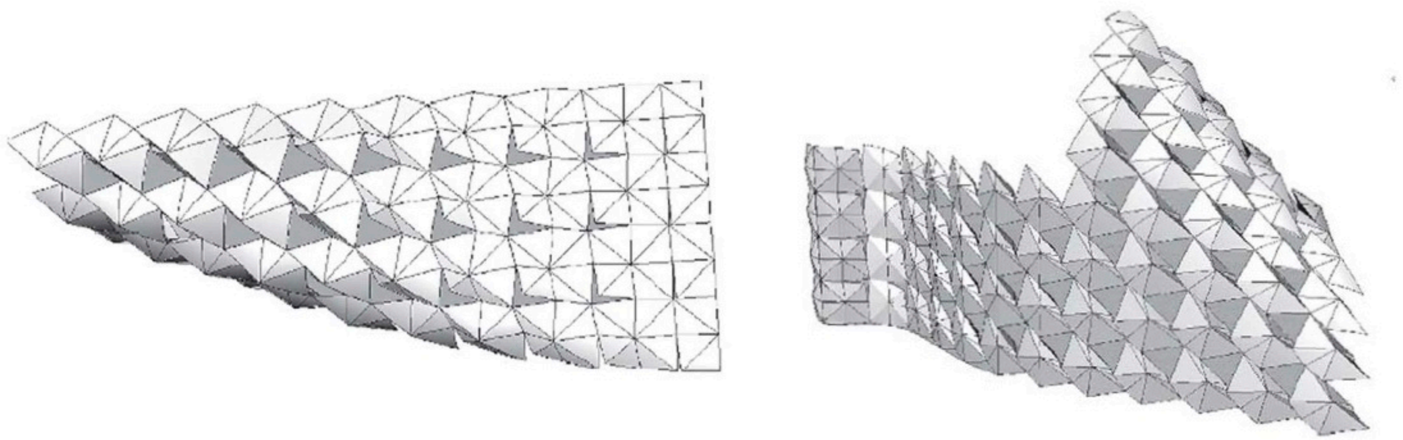


4b_

4a, 4b_ **Algorithmic description of forms and formworks (Richard Aeck and James Okelley).**





4b_

one variant to another, and the number of discrete variants found in each complete design, are emphasized more. A rather detailed tabulation of the wonderful complexity underlying growth in one dimension is given below; this account is given as a sample and part of a design curriculum aspiring to merge studio studies with generative systems, shape grammars and topological schemas and configurations. The three-dimensional linear growth and the corresponding configurations that can be built around it, are taken here as an initial foundation that allows the systematic exploration of the combination of the form and form-work with copies of itself in one dimension and facilitates their scripting and algorithmic definition.

3. Linear configurations

Spaces and spatial arrangements with one axis of growth are ubiquitous in nature and the arts. In the organic world this translatory symmetry, called by zoologists metamerism is quite frequent and suggests a part-to-whole relation where the whole consists of transposed, translated parts. In architectural design this translatory symmetry appears in any configuration that consists of identical parts along an axis such as serial modular spaces, colonnades, friezes, entablatures, row housing, high-rise apartments and so forth. And many a contemporary architecture and artistic production characterized by relentless repetitions of spatial cells, including skins, tiles, modules, textures and so on, may indeed be adequately described by these structures.

In all these cases, these patterns may be small or large, simple or complex, coarse or smooth, discrete or continuous, abstract or concrete, or they may be presented in full semantic terms, for example walls, staircases, shelves, slabs, entablatures, row housing, street networks, and so forth. Still there is always a difference between mathematical abstraction and patterns of appearance; the former are abstract, infinite, geometrical, numerical; the latter are concrete, finite, corporeal, subjective. The same dualism exists here too; in mathematics any pattern that has translations extends in infinity, but in reality no spaces are infinite, and most of what we perceive as spaces or objects, at least for design purposes, is finite. It is the process of recognizing underlying transformations that is of interest here, rather than the actual finitude or infinititude of the pattern.

In three-dimensional space there are six isometric transformations, three direct and three indirect. The three types of direct isometries are rotations about a center, translations along a line, and screw rotations along a line; the latter are products of translations along a line with rotations about a center in the line. The three indirect transformations are isometries that alter additionally the handedness of a body of space and they include reflections along a plane, rotor reflections about a center, and glide reflections along a line; the rotor reflections are products of reflections with rotations and the glide reflections are products of reflections with translations. Information about the isometric transformations and the ways they are combined with each other is captured in the definition of the various symmetry groups. The mathematical study of the groups has been given in many sources (see for example, Armstrong 1988). For some recent work pertaining to their applications in architectural discourse, see for example, Economou (1998; 2006), Din and Economou (2011). The symmetry groups can be additionally classified according to their translational structure and the dimensionality of the space that contains the transformations that belong in the set (March 1974). All symmetry groups are subgroups of the Euclidean group G consisting of all isometries, which is a subgroup of the similarities group S, consisting of all similarities. The ten symmetry groups Gij in Euclidean space, for i = the number of axes of translation and j = dimension of space, are given below.

G00	G01	G02	G03
	G11	G12	G13
		G22	G23
			G33

The complete enumeration of all the algebraic groups that comprise these ten structures has been carried out at different times, with different notations, and different agendas in mind. Nice accounts in the literature abound, see in particular, Shubnikov and Koptsik (1974). In the notation offered here the subscripts i and j provide an unambiguous way to discuss all these structures under a uniform labeling scheme. For example, within the convention of this scheme, G03 are the groups that capture the symmetry structures of three-dimensional configurations that have no translational structure, that is, configurations that have a center of symmetry; similarly G22 are the groups that capture the symmetry structures of two-dimensional configurations that have two distinct axes of translations, that is, essentially an infinity of emergent translations that fill out the plane. The structures of interest here are the G13 groups, that is, the algebraic groups that capture the symmetry structures of three-dimensional configurations that have one axis of translation, or alternatively, one axis of growth. These configurations appear in the literature with various names such as rods (Shubnikov & Koptsik 1974), fibers (Yale 1967), three-dimensional friezes and others. A detailed account of their formation can be found in Economou (2006).

A complete catalogue of all linear three-dimensional symmetry classes is given below in seven sets, the so-called symmorphic types, because the whole linear configuration retains the symmetry and form of the initial three-dimensional module that is repeated along the line. These symmorphic structures are followed by all possible non-symmorphic structures that can be extracted from those to produce a total of nineteen linear configurations in three-dimensional space.

The notation adopted here is the so-called non-coordinate notation for symmetry classes (Shubnikov & Koptsik, 1974). This notation indicates the number and types of symmetry generators and their corresponding spatial relationships. More specifically the symmetry symbols are: a rotation axis n of order n, a mirror-rotation axis ($2\tilde{n}$) of order $2\tilde{n}$, a reflection plane m, a translation axis a with an elementary translation a, and a glide reflection axis ($\tilde{a}$) with an elementary translation a/2. The signs between the symmetry elements denote the spatial relationships between the symmetry elements. The two-point sign (:) between two elements indicates that these symmetry elements are perpendicular to one another; the one point sign (.) in-

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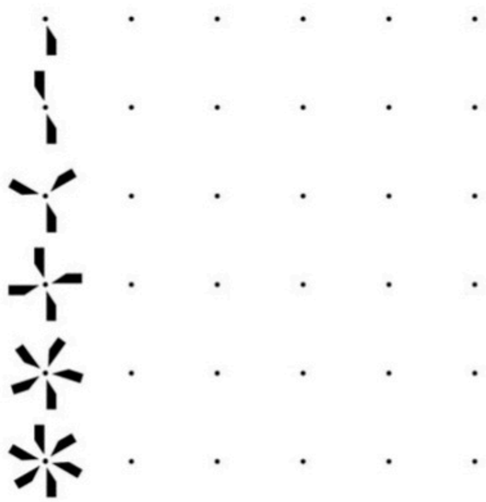


6a_

dicates that these symmetry elements are parallel to one another; lastly, an oblique-stroke (/) sign indicates that these symmetry elements are inclined to one another; still this last sign is not employed for the classes of design discussed here because an oblique axis to an axis of translation would generate a second axis of translation and therefore an infinite number of translations that fill the plane. These symbols are enough to describe the symmetry of any spatial configuration in three-dimensional space. For example, a pattern notated as 4 has one generator, the four-fold axis of rotation, and consists of four symmetries; a pattern notated as 4:m has two generators, a four-fold axis of rotation and a mirror reflection plane m perpendicular to the axis of rotation, and consists of eight symmetries; a pattern notated as a.4:m has three generators, an axis of translation a parallel to a four-fold axis of rotation and perpendicular to mirror reflection planes m, and consists of infinite symmetries.

There are various ways of representing symmetry transformations; for brevity and diagrammatic clarity here all symmetry classes are pictorially represented in an orthographic projection to render unambiguously the results of the applications of the transformations. The number of labels, represented here as chevrons, denote the number of identical parts in a configuration. Black labels denote the position of the label towards the viewer and white towards the back. All axes of transformations are assumed to be perpendicular to the plane of representation. Each configuration is typically denoted by a single module. Two or more modules side-by-side suggest an unfolded representation of the module; in other words, a module consisting of say, three repetitions of a motif of chevrons around three centers, means that the total module consists of the iterations of the modules represented horizontally and applied the one after the other. All configurations are enumerated up to the number of rotations $n = 6$. Diagrammatic representations of motifs consisting more than six rotations are left to the interested readers. The initial array of points / centers to capture all possible modules for configurations n ≤ 6 is shown in Figure 5.

3.1 n.a

The configuration n.a is generated by successive translations of shapes with symmetry n along their primary axis of rotation at a distance a. The combinations of the rotations n and the translations a, produce the screw rotations nj for $j < n$. A substitution of the symmetry axis n by the screw axis nj produces three types of subgroups nj, for ($j < n/2$), ($j = n/2$), and ($j > n/2$). The $j < n/2$ and $j > n/2$ classes are isomorphic; the first denotes a clockwise configuration, the latter a counterclockwise one. The $j = n/2$ is a neutral one in the sense that is simultaneously left-handed and right-handed. The four possible types in this category are the n.a, and nj for ($j < n/2$), ($j = n/2$), ($j > n/2$). A diagrammatic representation of these four types of patterns, for $n \leq 6$, is given in Figure 6(a)-(d).

3.2 2ñ.a

The configuration 2ñ.a is produced by successive translations of shapes with symmetry 2.ñ along their rotor reflection axis at a distance a. By definition this symmetry class occurs only for shapes that have a mirror-rotation axis of an even order 2ñ. There are no allowable substitutions in this category. A diagrammatic representation of the pattern 2ñ.a, for n ≤ 3, is given in Figure 7.

3.3 n:m.a

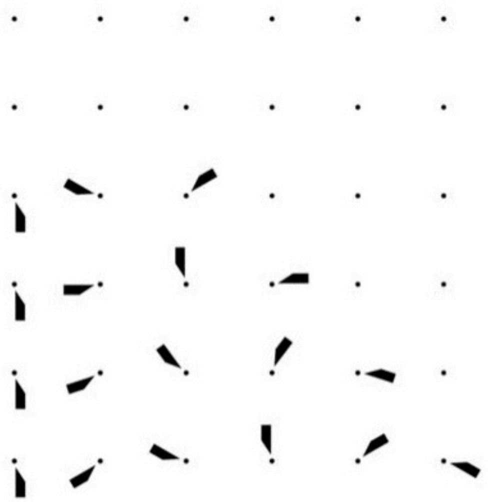
The configuration n:m.a is produced by successive translations of shapes with symmetry n:m along their primary axis of rotation at a distance a. The combinations of translations and mirror planes produces new reflections at distances a as well as at their midpoints at a/2. Other emergent symmetries include screw rotations and rotor reflections. A substitution of the symmetry axis n by the screw axis nj produces one more type of a subgroup nj:m for ($j = n/2$) or alternatively 2nn:m. The other two possibilities for ($j < n/2$) and ($j > n/2$) do not produce new types because the mirror planes are not part of the overall pattern. The two possible groups in this category are the n:m.a and 2nn:m. A diagrammatic representation of the two types of patterns, for $n \leq 6$, is given in Figure 8(a) - (b).

3.4 n:2.a

The configuration n:2.a is produced by successive translations of shapes with symmetry n:2 along their primary axis of rotation at a distance a. The products of the rotations n with the half-rotations produce new emergent half-rotations at distances a as well as at their midpoints at a/2. The combinations of the rota-

5_ A diagrammatic canvas to capture the symmetries of all linear configurations in three-dimensional space. The axis of translation is taken as perpendicular to the plane of the array. The horizontal rows denote rotational orders of symmetry (1,...6); the vertical columns denote repetitions of a motif along the axis of translation.

6a_ The six linear configurations 1.a; 2.a; 3.a; 4.a; 5.a; and 6.a based on the type n.a, for n ≤ 6.



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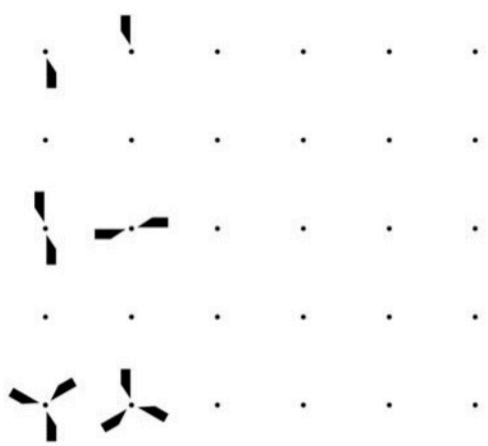

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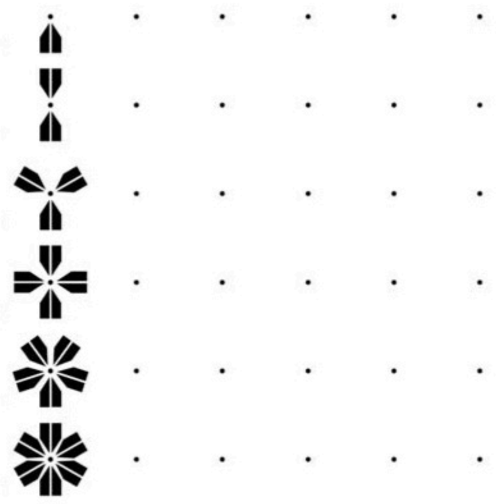
6b_ The four linear configurations 31, 41, 51 and 61 based on the type nj, for j < n/2 and n ≤ 6. The two additional cases of this type 52 and 62, for j = n-k, whereas n+1 < k < n/2 can be illustrated in a straightforward way.

6c_ The three configurations 21, 42 and 63 based on the type nj, for j = n/2 and n ≤ 6. These configurations are both clockwise and counterclockwise.



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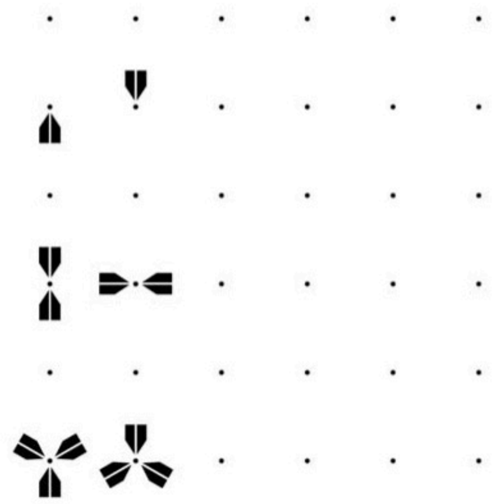

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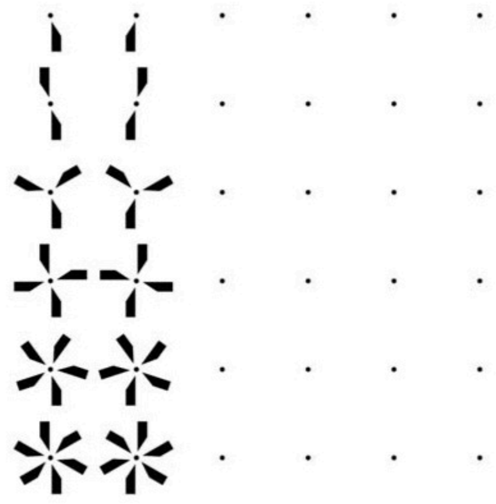

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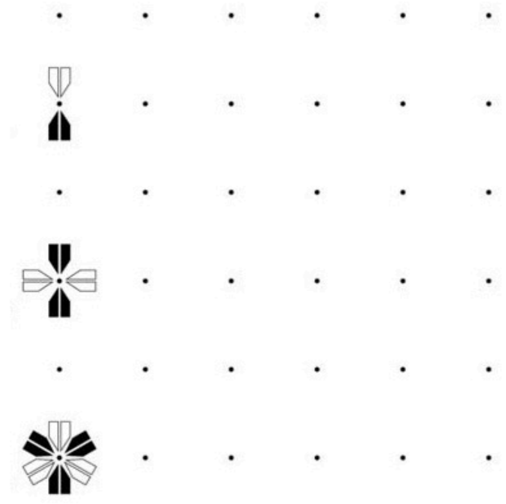


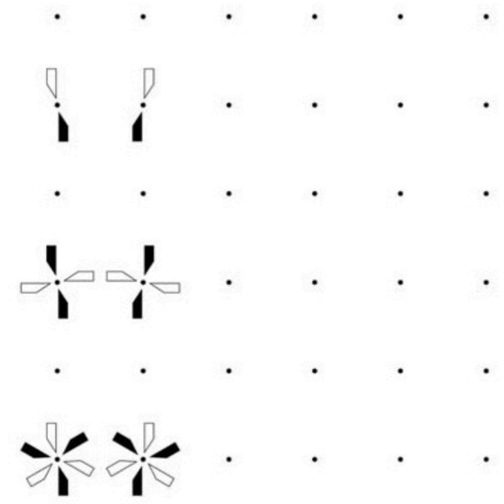
11a_

10a_ **The six linear configurations 1.m.a; 2.m.a; 3.m.a; 4.m.a; 5.m.a; and 6.m.a based on the type n.m.a, for n ≤ 6.**

10c_**The three types of linear configurations 21.m, 42.m; 63.m, based on the type nj.m, for n ≤ 6 and j = n/2 or alternatively 2nn.m and n ≤ 3.**

10b_ **The six linear configurations 1.ā; 2.ā; 3.ā; 4.ā; 5.ā; and 6.ā based on the type n.ā, for n ≤ 6.**

11a_ **The three linear configurations 2.m.a; 4.m.a and 6.m.a based on the type 2ñ.m.a for n ≤ 3.**



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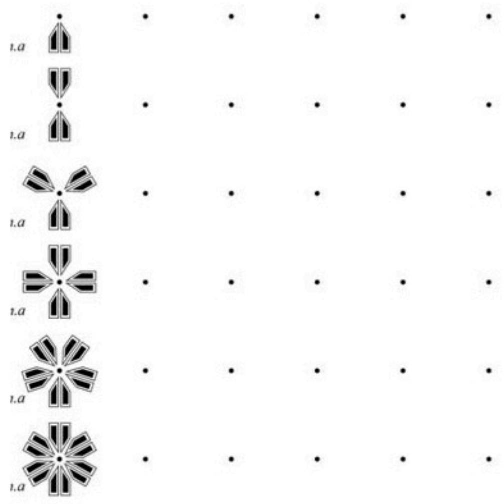

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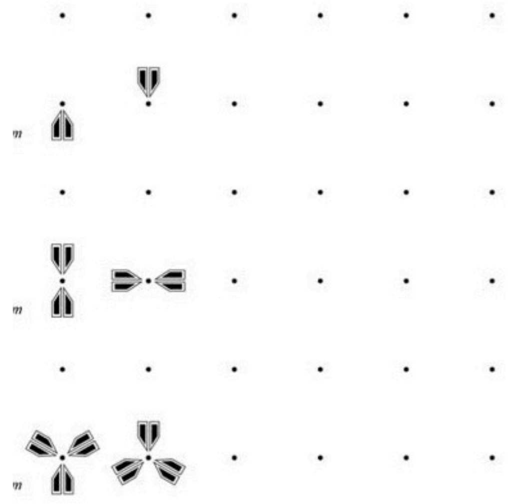

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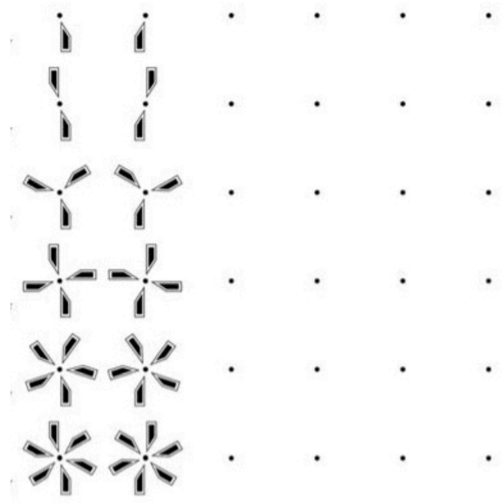


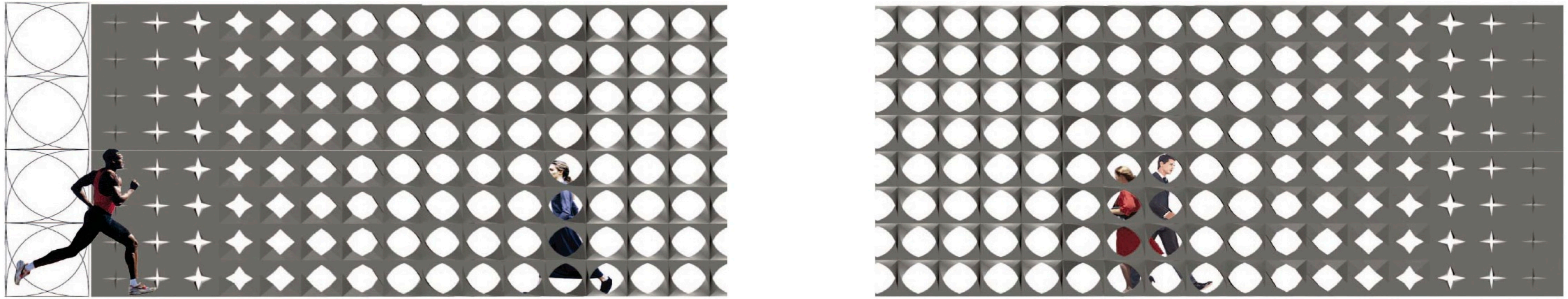
12c_

11b_ **The three linear configurations 2.a; 4.a; and 6.a based on the type 2ñ.ā, for n ≤ 3.**

12b_ **The three linear configurations 21.m:m; 42.m:m; and 63.m:m based on the type 2nn.m:m, for n ≤ 3 or alternatively, 2n ≤ 6.**

12a_ **The six linear configurations 1.m:m.a; 2.m:m.a; 3.m:m.a; 4.m:m.a; 5.m:m.a; and 6.m:m.a based on the type n.m:m.a, for n ≤ 6.**

12c_ **The six linear configurations 1:m.ā; 2:m.ā; 3:m.ā; 4:m.ā; 5:m.ā; and 6:m.ā based on the type n:m.ā, for n ≤ 6.**



tions n and the translations a, produce the screw rotations nj. Similarly to the first case of these symmorphic spaces, a substitution of the symmetry axis n by the screw axis nj produces three types of subgroups nj:2, for $(j < n/2)$, $(j = n/2)$, $(j > n/2)$. The four possible groups in this category are the n:2.a and nj:2 for $(j < n/2)$, $(j = n/2)$, $(j > n/2)$. A diagrammatic representation of these four types of patterns, for $n \leq 6$, is given in Figure 9(a)-(d).

3.5 n.m.a

The configuration n.m.a is produced by successive translations of shapes with symmetry n.m along their primary axis of rotation at a distance a. The products of the rotations n with the mirror plane produce new emergent mirror bisecting the angle of the rotation n, for n even number of rotations. Other emergent symmetries include screw rotations nj, and glide reflections ā. A substitution of the symmetry axis n by the screw axis nj produces the configuration nj.m for $(j = n/2)$ or alternatively 2nn.m. The other two possibilities for $(j < n/2)$ and $(j > n/2)$ do not produce new types because the mirror planes are not part of the overall pattern. A substitution of the mirror plane m by a glide reflection ā produces the configuration n.ā. The three possible groups in this category are the n.m.a, n.ā and nj.m, for $(j = n/2)$. A diagrammatic representation of these three types of patterns, for $n \leq 6$, is given in Figure 10(a)-(c).

3.6 2ñ.m.a

The configuration 2ñ.m.a is produced by successive translations of shapes with symmetry 2ñ.m along their axis of rotor reflection at a distance a. The products of the rotor reflections 2ñ with the mirror planes m produce new emergent half-turn rotations bisecting the angle of the mirror planes at distances a as well as at their midpoints a/2. Other emergent symmetries include glide reflections ā along the mirror planes at distances a. A substitution of the mirror plane m by a glide reflection ā produces the space 2ñ.ā. The two configurations in this class are the 2ñ.m.a and 2ñ.ā. A diagrammatic representation of these two types of patterns, for $n \leq 3$, is given in Figure 11(a)-(b).

3.7 n.m:m.a

The configuration n.m:m.a is produced by successive translations of shapes with symmetry n.m:m along the axis of rotation at a distance a. The emergent symmetries are many here because of the presence of the four generators and they include screw rotations nj, glide reflections ā, reflections m bisecting the angle of rotation n, reflections m along perpendicular mirror planes at distances a as well as at their midpoints at a/2. A substitution of the symmetry axis n by the screw axis nj produces the space nj.m:m for $(j = n/2)$ or alternatively 2nn.m:m. The other two possibilities for $(j < n/2)$ and $(j > n/2)$ do not produce new types because the mirror planes are not part of the overall pattern. A substitution of the mirror plane m perpendicular to the axis of rotation n by a glide reflection ā produces the space n.ā:m. The three configuration in this class are n.m:m.a, 2nn.m:m, and n.ā:m. A diagrammatic representation of these three types of patterns, for $n \leq 6$, is given in Figure 12(a)-(c).

Discussion

A major motivation underlying this work is the exploration of the relationship between visual design and construction as it is typically entertained in an architectural design studio setting and its critical comparison to mathematical frameworks supported by formal studies in design topologies, configurations and generative schemata. Languages of design are generated by all different kinds of rule-based systems including shape grammars, cellular automata, L-systems and so on (see for example, Stiny 2006); configurations are similarly explored to discern what is structurally possible in a design context (March 1998; Economou 1999). Both provide a complementary insight in design explorations and both suggest alternative ways to tackle and unravel complexity in design. The work here oscillates between both ad hoc views of design and systematic studies and attempts a first comparison by relating the casts and forms with a specific configurational problem, the class of three-dimensional spaces characterized by an axis of growth. The nineteen types of algebraic group structures that capture the properties of these configurations were briefly described and illustrated to show the expressive power of the structures of these spaces. A sample design based on the parametric definition of a single cast using the four-fold configuration and its systematic employment at various scales to produce a complex undulating recursive surface is given in Figures 1 and 13.

13_ **Sample of the cast modules and the prototypes developed (Lorraine Ong).**