Patterns of Shape Design

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Abstract: A fundamental problem in processing 3D shapes is insufficient knowledge engineering. On the one hand there are numerous methods to design and manufacture 3D shapes in the real world. On the other hand, numerous digital methods for representing and processing shape have been developed in computer graphics. Most of these methods make certain assumptions about the kind of 3D objects that they will be used for: A surface smoothing algorithm, for instance, is not well suited for assemblies of rectangular blocks or for pipe networks. However, it is currently not possible to *formulate* the properties of a given shape explicitly in an commonly agreed way.

This paper is a first step towards classifying structural descriptions of man-made shape. By listing construction principles and principles for their combination it follows a phenomenological approach. The purpose is to illustrate the inherent complexity of the domain, and to lay out the foundation for subsequent thorough knowledge engineering.

Key Words: shape semantics, design patterns, shape design, man-made objects
Category: I.2.4, I.3.6

1 Introduction

The goal of this article is to prepare the grounds for semantically richer methods of describing the properties of 3D shapes. It is necessary to build a sustainable bridge between the fields of *knowledge engineering* and *shape processing*.

Shape processing algorithms typically make implicit assumptions about the properties of a shape. The signal processing approach to surfaces, for instance, understands surfaces as 2D signals, and *frequency bands*, i.e., high- or low frequencies of a surface, are important concepts. *Symmetry detection* algorithms reveal the structure of architectural buildings, some can even deal with deformed bodies of humans or animals. *Instance detection* algorithms find identical objects and sub-objects in unstructured triangle meshes (more examples in sec. 2).

These *shape analysis* algorithms can identify detailed shape properties. This could deliver important information for subsequent *shape processing* by using a markup facility for explicit description of shape properties. However, the analysis algorithms suffer from the inability to store their results in an explicit way.

It would be very useful to have a more sophisticated and differentiated *shape vocabulary* for describing semantic properties: shape algorithms could be applied to only those parts of a heterogeneous 3D model that they are designed for.

The dominant method today for describing shape is as a list of low-level geometric primitives, i.e., point clouds or triangles for sampled (scanned) surfaces, or parametric surfaces like NURBS or spline patches in industrial applications. These geometric primitives have no semantics attached: Sophisticated reverse engineering is necessary, e.g., to determine that a given "triangle soup" describes in fact a pipe network, a collection of boxes, or a bent sheet of metal.

An idea for solving this situation came from the observation that there are not all too many fundamentally different ways of manufacturing man-made shape.

1.1 Motivation: Design Patterns

The original motivation for this paper came from a seminal book in software design, *Design Patterns, Elements of Reusable Object-Oriented Software* from the *"Gang of Four"* (GoF), Gamma, Helm, Johnson and Vlissides [GHJV95]. It is based on the observation that experienced programmers tend to think in certain patterns when solving complex software design problems. The GoF names 23 patterns, 14 of which have become really standard since 1995 – and hundreds, if not thousands of more specialized patterns have been developed since then.

Some interesting parallels exist between software design and shape design. Shape professionals also need to solve the complex design problem of conceiving a 3D object in a way that it (i) fulfills its functional specifications, (ii) can be manufactured, (iii) is physically sufficiently stable, (iv) aesthetically pleasing, and (v) not too expensive. In addition to their creativity they have a certain pool of proven methods and techniques that they can apply and combine to reach these goals. Consequently, all man-made shapes exhibit a certain regularity. Our hypothesis is that most of the abundant variety of existing shapes is created using only a limited set of fundamental shape design patterns.

Just as is the case with software design patterns, the value of shape design patterns would be to facilitate the communication about shape. The idea is to replace the current technology-driven by a purpose-driven shape terminology: Instead of technical concepts like voxel spaces, moving least squares or adaptively sampled distance fields, well known in the graphics community, one could emphasize, and express, the difference between cast, forged, and milled shapes, or the pros and cons of class-A design versus block design. Consequently, the pre- and post-conditions of shape processing algorithms, of shape conversion and retrieval, could be formulated in purpose-driven terms.

We would like to use *shape-related ontologies* to make the fact explicit that, e.g., a concrete shape (Cheops pyramid) is one instance of an abstract shape family (four-sided pyramid). The great challenge is that a universal shape ontology must in fact be very elementary and basic: To be more generally applicable than any domain-dependent ontologies, it must consequently be amenable to and useful for non-experts, i.e., for ordinary human beings from all cultures.

1.2 Conjecture: Shape Design is Rule Design

A simple experiment reveals how constrained the capacity of human beings to design shape really is: The task is just to *take a pencil and to draw about two dozen points on a blank sheet of paper.* The proband may choose to arrange the points in any way he or she likes. – One might think that the outcome of the task is pretty arbitrary. However, it is not; Fig. 1 shows some typical results.

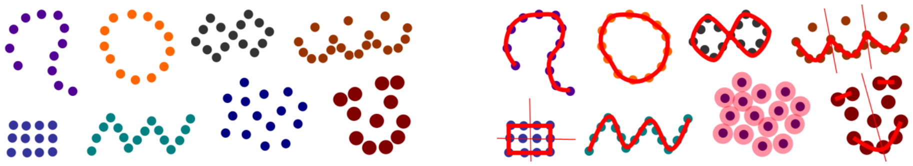

Figure 1: The **place-the-dots** game. Left: Typical "arbitrary" dot patterns produced by average humans. Right: Underlying design principles.

The proband apparently immediately designs a rule, rather than only one shape. It is obviously a good idea to partition the obtained designs into classes of similar basic patterns. This leads to the conjecture that every human-designed shape is inevitably an instance of a more general shape class with many variations. The "variation directions" correspond to the dimensions of the shape's design space. In that sense, designing a shape inevitably means in fact designing a rule.

1.3 Determinants of Shape Design

A taxonomy of shape design methods must take into account the following factors that influence the shape of a physical object:

- **Design intent** subsuming function, purpose, semantics, meaning, significance: A pillar and a pipe have different meanings but are both cylindrical. Very different objects can have the same shape.
- **Planning tools** and their expressiveness limit the space of realizable objects: Things that can not be planned can not be built. Things that are easier to plan are more likely to be built.
- **Fabrication constraints** determine which of the ideas and plans can be transformed into real-world objects in a commercially viable way.

The interplay between those factors is complex. Intelligent design solutions can turn fabrication constraints into stylistic features: timber framed buildings, romanesque churches and roman aqueducts are examples of styles also resulting from limitations of fabrication technology. These limitations also influence the *space of conceivable shapes*: Shape professionals obviously do not waste their time conceiving shapes that will never be realized.

2 Related Work

Ontologies for shape processing have so far primarily followed a part- or feature-centric approach. A larger initiative pursuing the vision of *shape ontologies* was the Aim@Shape project, a FP6 Network of Excellence funded by the European Commission [AIM06]. It was inspired by a school around Bianca Falcidieno and Michela Spagnuolo. They propose, e.g., in the context of shape retrieval, the notion of a *shape prototype* represented as attributed graph with nodes containing descriptors for local shape features, so that searching can be mainly reduced to graph matching [BMSF06, MSF07]. Albertoni et al. [APP$^+$05] present the Aim@Shape *Digital Shape Workbench* framework for shape search with domain-dependent ontologies. In this spirit Camossi et al. [CGM07] present an ontology for the functionality of shapes with derivations, e.g., of the following kind:

Product → Functionality → FunctionalArea → FormDescription
FormDescription → (PatternInfo, HoleInfo, StabilityInfo, SymmetryInfo)

The functionality is derived again from shape decomposition into features such as convex or concave areas or tubular areas, etc. Cheutet et al. [CCG$^+$06, CLC$^+$06] (also Aim@Shape) support the shape design process with domain-dependent ontologies. Their 2D sketching tool "knows" about the typical feature lines of a car, so that user can assign a meaning to a 2D sketch, which is further processed using a shape grammar. An interesting approach for the simplification of large CAD models ist presented by Posada et al. [PTWS05]. They use ontologies to generate different views on a given model, e.g., for an engineer or for a management person. This requires the recognition of shape parts, e.g., tube structures or connectors, which are replaced by simplified parts, left away, or shown in detail to generate the different views.

In contrast to these feature-centric approaches we aim at a procedural description of shapes, taking into account the assembly and manufacturing process. In any case the goal is to find atomar shape building blocks. However, we argue that shape features (*convex part*) or CAD features (*bore hole*) are generic but may be too fine-grained, whereas functionality (*gearbox*) is too coarse-grained, and in fact a domain-dependent interpretation. Shape design patterns might be a reasonable view in between low-level local features and high-level functionality.

3 A Catalogue of Patterns of Shape Design

The following list of shape design patterns is not a true taxonomy: It is reasonably comprehensive, but it is still incomplete. It is partly overlapping, and it provides no hierarchy of sub- and sub-sub-methods. There is also no distinction between generic principles, used by humans since ages, and technical fabrication methods; most patterns have both aspects. – They are still very useful because (i) they are elementary, and (ii) they reflect the complexity of shape design.

3.1 Block Pattern

Arrangement of primitive objects from a fixed set of combinable prototype building blocks, usually rectangular boxes, but often also cylinders, spheres, cones etc. Objects may touch but do not intersect, and they are typically aligned (grid).
Examples: LEGO, brick walls, toy bricks; overall structure of many buildings

3.2 Bending Pattern

Flat, connected sheet (or wire) of material which can be bent smoothly (or sharply), but can not be stretched. Mathematically, bent sheet are *developable surfaces*, any surface point has one tangential direction with zero curvature.
Examples: Paper craft models, bent sheet metal, but also strip of flat panels

3.3 Trimming Pattern

Trimming is cutting a hole out of a (possibly curved) surface, or just marking a potential hole. The boundary of the hole is called *trim curve*. The trim curve may be defined implicitly, e.g., from two 3D objects overlapping in space.
Examples: Sewing patterns for dressmaking, blanking, punching, hole cutting

3.4 Tubular Design Pattern

A tube is basically a curve in space with constant thickness (radius). A pipe is hollow inside, requiring also an inner radius. A more general sub-type with variable cross section profile is called *sweep* or *generalized cylinder*.
Examples: Scaffoldings, pipe networks, support structures of freeform buildings

3.5 Layer Pattern

Multiple layers of different materials, or of materials in different orientations (*anisotropic materials*), stacked on top of on each other. Layer thickness can range from thin to thick, but it is mostly constant over the covered region.
Examples: Ply wood, multi-layer walls, material deposit; pearl, tree bark

3.6 Pressure Pattern

Deforming a piece of material by strong force, temporarily or permanently. Can be done with positive and negative forms (dies). They may affect one side only to inscribe a pattern (coining). Not meant: Trimming or injection die casting.
Examples: Pressing car parts, like engine hood, from sheet metal; crash test

3.7 Repetition Pattern

An object or operation is repeated over regularly spaced intervals. Very general principle, can be just 3D copy-translation-paste, or a multi-stage industrial manufacturing process applied in regular intervals to a workpiece. Typical is linear repetition, but it can also be applied along a curve (circle: radial repetition). Sub-types of repetition are 1D curved sequences and 2D grids or tilings.
Examples: Garden fence, stories and windows in a facade, holes in a ventilation grille, tongue-and-groove panels; stairways of all kinds; car rims

3.8 Symmetry Pattern

Right and left parts become congruent when a reflection operation is applied. Often uses a straight symmetry plane, but can also be more general: Deformed body, point/radial symmetry. Symmetries can be nested (double symmetry).
Examples: Building facades, furniture, ornaments; animals; road pavements

3.9 Material Removal Pattern

Taking away material successively, e.g., by means of a moving tool. This has a volumetric aspect when much material is removed, e.g., with deep intrusion, and a finishing aspect when the surface is modified only slightly.
Examples: Sculpting a statue using a chisel, milling a shape out of a block; machining (metal), grinding, abrasive cutting; drill hole, bore hole, digging

3.10 Erosion Pattern

Material is displaced under the influence of a constant force or a material stream acting on the surface. This has a smoothing effect in that peaks and spikes are flattened out, and ridges and grooves are successively filled with material.
Examples: Erosion of mountains under the force of weather and gravity

3.11 Local Growth Pattern

A surface continuously deforming outwards forming bumps or elongated structures. May be repeated on smaller scale to form a network of branches. Although usually continuous, it can be conceptually seen as a local replacement operation.
Examples: Animal growth, plant growth, growing street networks in a city

3.12 Fair Surface Pattern

Highest-quality curved surfaces, often visibly exposed, with elaborate finishing. The curvature must vary smoothly, without jumps or creases (scale dependent), but may incorporate feature lines (*creases*). Fair surfaces are usually subject to design considerations, requiring visually pleasing shadow lines and reflections.
Examples: Visible parts of consumer goods; hulls of cars, ships, airplanes

3.13 Clothoid Pattern

Curve segments with smoothly (linearly) increasing (or decreasing) curvature are used in road and railway design. Prototype is the spiral, special case is the circle. Also used as section curves for curvature control in high-quality surfaces.
Examples: Curves that allow turning the steering wheel at constant speed

3.14 Sectional Design Pattern

Section curves are typically drawn on a set of parallel 2D planes in space. Consecutive sections are connected with a smooth surface (*lofting*). For controlling complicated free-form surfaces, also planes in arbitrary position are used.
Examples: Architectural and engineering drawings (front, side, top); ship hull design, aircraft wing design; computer tomography

3.15 Extrusion Pattern

A surface part is cut out and lifted (*trimmed offset surface*), and the sides are closed by a side strip of constant width. The extrusion height can also be negative (*inset*). Extrusions can be very long, so that the side strip is dominating.
Examples: All kinds of profiles; aluminium profiles, double-T-beam

3.16 Casting Pattern

Filling a prepared cavity (negative form, *mold*) with liquid material that solidifies. The mold is removed by destruction, or it is opened and pulled away (may be complex), which severely constrains the shape (3° demolding angle etc.).
Examples: All plastic parts of consumer goods; cast metal, cast concrete

3.17 Suspension Pattern

A suspension shape is formed by elements only subject to tension, not compression or bending. A hanging flexible chain forms a *catenary.* An inverted catenary is the arch shape with zero shear forces between stones. A suspended thin surface is deformed only by gravity and by the outward pulling forces at its boundary.
Examples: Suspension bridges, tents, tensile architecture, bicycle wheel

3.18 Forging Pattern

Successive local deformations by means of a hammer. Forging reduces thickness, so it always starts from a more compact shape to obtain a more stretched out shape. Localized pressure design, with greater control and design freedom.
Examples: Wrought iron fences, gates, rivets, and chains, goldwork, gold foil

3.19 Congealing Fluid Pattern

Locally modifying the solidification of a fluid (or the melting of a solid) by applying force (pressure), temperature, electricity, or chemicals. The resulting surface is very smooth and resembles that of a viscuous fluid.
Examples: Lava, dripstone, glass blowing, soldering

3.20 Lathe Pattern

Material is successively removed from a spinning block using a fixed (but movable) cutter. The result is a *surface of revolution*, i.e., a 2D curve rotated around an axis. Material can also be added to obtain such a revolved shape.
Examples: Knobs, table-legs, decorated bars, everything that needs to spin with precision, but also pottery (potter's wheel)

3.21 Design by Similarity Pattern

A shape is designed by taking another shape as model. The source shape is not simply copied, but adapted to new requirements. Used to create a new member of a shape family, or to adapt a shape to look as if belonging to that family.
Examples: All doors look alike, hidden doors resemble the wall; the Atomium (Brussels) looks like an atom, the Cheops pyramid resembles an ideal pyramid

3.22 Motion Path Pattern

A shape is determined by the necessity of another shape to be able to move. The free space is often formed by the moving shape in all its allowed positions. A shape may also constrain a motion, so that only allowed positions can be taken.
Examples: All doors, drawers, elevators, vehicles; rails, moving rods, hoists; roads, pathways, corridors; all assemblies that allow dis-assembly

3.23 Offset or Frame Pattern

A fixed-with strip runs along the boundary of a shape, like a frame or a band. The strip can be realized in various ways. At corners, it may join sharply (miter, angle bisector) or rounded. This pattern is often used together with extrusions.
Examples: Frames and framings, decorative profiles, front sides of furniture; pavement around a building, or along a road

3.24 Edge Decoration Pattern

Visual emphasis of an edge by applying a profile, from simple bevel to a doubly-curved cyma (applied using a router). Even more complex are decorative mouldings in architecture with concave profiles and repeated ornamental decorations. **Examples:** Beveled, chamfered, rounded edge; waterfall, bullnose, triple edge; Cavetto, ovolo, cyma, ogee molding; Kyma ionico, rope profile, meander

3.25 Clay Pattern

Deforming a homogeneous material with high plasticity. Volume is preserved, but may also use cutting and coalescing. The shape can be deformed using a wide range of *clay modeling tools*, but also with bare hands (low precision). **Examples:** Initial stage of designing industrial shape; artwork; clay huts

3.26 Weaving Pattern

A flexible band (weft) is interlaced horizontally with vertical support bands (warp), alternatingly one being in front of the other. The resulting structure can be quite stable. Very complex spatial weaving or knitting patterns are possible. **Examples:** Knitting, textiles, shape weaving; baskets, woven furniture (Rattan); rebar grids for reinforced concrete; braiding, to wattle hair

3.27 Hollow Shape Pattern

The shape of an empty space is often carefully designed, since solid objects and free space complement each other. Architectural design often starts in fact by designing the empty space, and to successively group solid objects around it. **Examples:** Rooms, corridors, halls, cavities, air ventilation

4 A Catalogue of Composition / Decomposition Patterns

Real-world objects are typically designed using not a single, but a combination of multiple design patterns, possibly employed on different levels. The overall shape might follow a different pattern than detail solutions on a smaller scale. In fact, when performing the exercise of decomposing a number of real-world objects into the patterns used for designing them, one will quickly realize that the combination of patterns itself follows certain patterns. Some of these *composition patterns* are presented in the following. – Note the parallel to the *pattern of patterns* in software design introduced by the GoF [GHJV95].

4.1 Style Pattern

A style is a preset of design decisions to make sure that similar design problems are solved in a similar, consistent way. A style is typically a collection of distinctive patterns that allow various ways of combining them (*style elements*).
Examples: Greek style, Romanesque style; ionic, doric columns; timber frame style, Art Deco; Gothic style allows constructions only with compass and ruler

4.2 Partitioning Pattern

For functional, technical, aesthetic, or manufacturing reasons it can become necessary to split up a larger shape into smaller separate pieces. The gaps between the parts is typically filled in a systematic way, e.g., using the seam pattern.
Examples: Doors and windshield of a car are separate pieces, but conceptually they form part of the seamless car's exterior design surface; a computer mouse should fit the natural shape of the hand, but it is not manufactured as one part

4.3 Seam Pattern

Direct connection of separate shapes along a common edge or boundary. For functional, technical, aesthetic or manufacturing reasons it may be necessary to connect separate parts tightly. A special case of a seam is a visible gap (*interstice*) that is kept intentionally, e.g., around a car door.
Examples: To sew, weld, bind pieces together; basted, bevel, bond, and brazed seams, also building seams; connecting overlapping metal sheets with bolts

4.4 Blend Pattern

A transitional shape connecting two or more separate shapes. A smooth blend matches neighbouring shapes as seamlessly as possible (*tangent-, curvature continuity*). A decorative blend detracts from a crack by emphasizing it. A concealing blend continues the structure of the surfaces to become indistinguishable.
Examples: Stucco blends between wall and ceiling; a rolling-ball blend connects smooth surfaces with tangent continuity; separate walls can be seamlessly blended by applying the identical plaster to them and to the blend

4.5 Assembly Pattern

Agglomeration of separate pieces that are designed to fit together. Pieces are joined permanently (gluing, welding), or non-permanently (screws). Special case are articulated assemblies (mechanisms) with parts designed to move.
Examples: All machines, almost all industrial goods

4.6 Penetration Pattern

One shape gives way for another, physically or just conceptually. Physical penetration requires removing a part of one object, or of both (creating an aperture, cutting away some part). Conceptual penetration occurs when a part of a shape looks like a separate shape, or as if it was part of another shape.
Examples: Holes for pipelines, power lines, supporting beams, downpipes; elevator shafts, staircases; openings, passageways, undercrossings; woodworking joinery, e.g., dovetail joints to connect wooden boards

4.7 Guiding Structure Pattern

Often a larger conceptual shape is not realized directly as one physical object, but it is employed only as a guide for the placement, orientation, and alignment of smaller structures. In many cases a reduced, more abstract underlying shape is used for designing or dispersing numerous concrete shapes.
Examples: Overall shape of a building, car, machine; U- and L-shaped buildings; stadium, amphiteatre; bricks forming a curved wall; graph of street network; often perfect mathematical shapes are used as model for an (necessarily imperfect) physical shape; example: circle vs. round arch, also Cheops pyramid; geometrical gardens (French Renaissance), tree shaping, shrub shaping (*topiary*)

4.8 Systematic Variation Pattern

A set of shapes that are all different but share major design features. One reason is to obtain a coherent appearance but to avoid simple copying, another is changing purpose. A simple case is repetition with systematic parameter variation (width, height), but variations can also be much more complex and subtle.
Examples: Garden fence with planks of different lengths so that ends form a curve; story variations in a decorated facade; areas with homogeneous building styles; the off-road version of a family car; Gothic windows with *window tracery*

4.9 Hierarchy of Shape Design Patterns

Decomposition of a large complex object into sub- and sub-subparts, according to functional, technical, aesthetic, or manufacturing criteria. Each part can employ its own pattern of shape composition (inner nodes) or shape design (leafs). This yields a *part-of* hierarchy created either in a bottom-up fashion (aggregation), or top-down (decomposition); in practice often a mixture is used.
Examples: Aircraft carrier, oil platform, space station; engineers, and also 3D artists, work in a coarse-to-fine manner, from overall shape to small-scale detail

4.10 Hierarchical Replacement Pattern

Schematic shape hierarchies can be described using symbols and replacement rules (*shape grammar*). Every shape carries a symbol, and rules specify how a shape with one symbol is replaced by sub-shapes carrying other symbols. Often the union of the sub-shapes occupies the same space as the replaced symbol.
Examples: Floor layout, facades of buildings; urban land use; aircraft design

5 Conclusion and Future Work

We have performed the tedious exercise of analyzing the structure of numerous real-world shapes, and compared them with manufacturing technologies and geometric modeling methods. As a result, we have identified a set of 27 patterns of shape design and 10 shape composition patterns.

The patterns are designed to be as universal and generally applicable as possible. Their claim is that they are immediately understandable by basically everybody. This is an important step towards making also *shape ontologies* readily understandable and, thus, to support their proliferation in mass market compatible standards, applications, and file formats.

However, this exercise was just the beginning since the patterns now have to prove their expressive power in practical applications, for example:

- **Case studies in shape analysis**
  More experience must be gained in applying the pattern scheme. A major challenge is ambiguity: A stairway may be seen as a sequence of individual stairs (repetition), but it may also be seen as massive block of cast concrete.
- **Formal ontology for shape design patterns**
  Some formalization is needed to make the scheme amenable to algorithmic processing. It may be difficult to map it to standard ontologies because of its procedural and parametric nature, and the interdependencies and ambiguities.
- **Recognizing the function of a shape**
  The stability of an armchair may come from carved wood, welded metal tubes, or injection-cast plastic. Seat and armrest, however, are smooth, finished surfaces of a certain size; so design patterns may indicate the function of a shape.
- **Shape editing by pattern correspondance**
  Once the used patterns are identified, they can be edited or replaced. A sequence or a grid can be replaced by another, seams by bonds, assemblies by cast solids. A smooth surface can guide a curved grid, or vice versa.

We hope that the shape design patterns inspire a new *decompositional* view on everyday shapes around us, one that keeps asking: ***How is this thing made?***

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