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INTERACTIVE VISUALIZATION FOR THE COMPARATIVE ANALYSIS OF LIFE CYCLES IN COMPLEX PRODUCT DESIGN

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Abstract

A trend in engineering design is, that product models have significantly increased in detail in the past and this trend is likely to continue at even a higher rate in the future. This trend also includes data on the life cycle of a product, such as the direct and indirect inventory, costing data, production process data, consumer behavior data and others. If the available product data is to be used effectively to understand interconnection, consequences of decisions across many levels, then this data needs to be processed in a manner which supports humans cognitive abilities. It is therefore proposed to integrate visualization methods into a systematic LC data acquisition environment. This will be used for the comparative analysis based on (old or optimal) reference products or on thresholds checking the compliance to legal limits. A special class of interactive, three-dimensional geometrical objects, namely OM-Glyphs has been developed together with appropriate functions and mappings to represent LCI parameters and LC data of complex products within an interactive rendered three-dimensional information space. With this novel approach, newly introduced to LC related design analysis, activities such as evaluation of design parameter variations and their impact on the LCI and search for and analysis of patterns being either stable or affected, could be performed much easier, faster and efficient than with any traditional methods in this field currently available

Keywords: product design analysis, life cycle assessment, information visualization

1. Introduction

The fairly data intensive nature of today's (product) designs including also to an increasing amount LC related information, even for simple products, quickly requires the utilization of various methods and modern information technology to store, retrieve and represent a vast amount of information [1,2].

In particular within product design analysis and life cycle assessment, tools to support an efficient man-machine dialogue and to help an expert analyzing calculated results are either not available or leave much to desire left. Especially recent, quite promising results made in information visualization, the computer-aided use of visual processing to gain understanding while providing for a comprehensible display of multi-dimensional data has been neglected in almost all (design) analysis and LCA related systems currently available. The approach discussed in this paper to address the aforementioned problem of information visualization is also thought to be suitable for representing life cycle costing data, thus allowing an efficient and simultaneous assessment of environmental and costing aspects.

2. Product design analysis and LCA

2.1 Problems and scope

The main objective of visualization is aiding understanding. And understanding in this context is vital for interpretation, which is an integral part of modern LC related analysis and assessment methods (cf. [3,4,5]). In both interpreting the inventory and environmental impact assessment results while trying to find correlation and relationships to design parameters, there is considerable scope for developing specialized visualization methods.

Information of product designs containing or being linked to LC related data is vast, uncertain and therefore complex. The traditional methods of representing such information as life cycle inventory (LCI) and environmental impact assessment (EIA) data is to utilize e.g. tables, xy-graphs, bar charts, pie charts and various 3-dimensional variants of those (cf. example of LCI information in figure 1). However, it is felt, that these methods do not address sufficiently the following aspects. First, representing basic LC related information at-a-glance. Second, filtering out data, while summarizing the filtered data (so as to reduce the information load). Third, providing structures and functionality to support interactive interaction of users with data represented during computer-aided analysis.

Three-dimensional geometric objects (so called glyphs) were utilized to address these problems. Spatial location, shape, color, etc. are the control parameters used to represent data, resulting in objects with a characteristic shape, size and color depending on the data. The advantage of utilizing glyphs is that they allow a user at a glance to see major contributors to the life cycle, while at the same time understanding uncertainty and the contribution of the filtered-out data. This is especially useful when trying to understand the interaction of components in complex product designs. A prototype software was developed to demonstrate the concept and a case study on a complex product is used to show the functionality.

2.2 Related work

The use of icons or glyphs to create abstract visualizations of (multi-dimensional) data sets is based on human perceptual abilities. Different parameters describing spatial, geometrical and retinal properties of such icons or glyphs defining their position, orientation, shape, color, etc. are commonly used to encode more information in a comprehensible format, allowing multiple values to be encoded in those glyph parameters [6,7]. The visualization of icons and glyphs is based on the concept of marks such as points, lines, areas, surfaces and volumes and their graphical properties [8,9]. First technical applications, exploiting the effectiveness of iconic and glyph-based visualization that is due to the human eye-brain system's ability to discern finely resolved spatial relationships and differences in color, texture and shape, appeared in the field of engineering mechanics [10,11]. Further applications successfully employing information visualization in fields, other than those mentioned above, can be found in [12,13,14,15]. Work on information visualization taxonomy and the systematic analysis of point designs in this field accompanied by numerous examples and a well compiled list of reference literature can be found in [16,17].

3. LC related information visualization and glyphs

3.1 Overview

Visualization techniques provide tools for quickly and efficiently obtaining information from data. These may range from basic presentation techniques just displaying the data in a plain way, up to quite sophisticated techniques, which are capable to extract, map and finally display an information set automatically. Within the scope in this paper, we will focus on the use of the latter, employing the particular technique of glyphs, acting as symbolic representation to show essential characteristics of a data domain to which they are linked to. With this visualization concept, replacing original data by a carefully designed symbolic, interactive display, which features a better structured and compact, hence more clear and meaningful representation, well-known advantages of glyph-based information visualization already experienced in other technical applications, shall also be made available to the LC related analysis of product designs.

Before one is able to apply glyph-based information visualization for a concrete example, the entire structure of a set of glyphs according to information subject of visualization and their appearance need to be specified. First, the glyph's number of degrees of freedom, i.e., the parameters or so-called *glyph attributes*, which can be varied and separately linked to data of a known context, need to be fixed. Second, the *symbolic appearance* of the glyph itself, i.e., its structural generation needs to be specified. This is done by determining the way characteristic values of a precomputed information set are mapped onto the glyph's attributes. This process, a kind of data abstraction, provides an excellent, by its nature quite natural, opportunity to enrich their semantics. Third, its actual visualization on a computerized device using its specified (generic) structure needs to be defined and *linked to actual data* (streams) of precomputed characteristic values.

3.2 The structure of OM-glyphs

The set of glyph attributes that defines the number of degrees of freedom, i.e., a glyph's set of control parameters can be divided into 3 major groups. First, *spatial parameters* that define position and orientation. Second, *geometrical parameters* that define the shape. Third, *descriptive parameters* that define color, transparency, opacity and saturation. Thus a glyph's degree of freedom can be specified as a domain consisting of a cross product of a spatial, a geometrical and a retinal domain. Information of a field or discipline subject to analysis and visualization can be abstracted as a *reference domain*. A selection of these data (the reference domain), which is important or relevant in some respect can be abstracted as a *selection domain*. The space in which a glyph exists can be abstracted as its *appearance domain*.

Throughout this paper we assume that the bound, closed point set $\mathcal{E}$ of an ellipsoid $e \in E$ is defined by a quadratic equation

$$\boldsymbol{x}^T A\, \boldsymbol{x} = 0 \tag{1}$$

within the Euclidean point space $\mathbf{E}^3$ where $\boldsymbol{x} = (x,y,z,w)^T$ are the homogeneous coordinates of a point in 3D space and A is a symmetric coefficient matrix. To describe ellipsoids that are attached to either an ellipsoid or a sphere that is located at the center of a glyph, equation 1 is rewritten by introducing a displacement of the ellipsoid center as shown in equation 2 below

$$(\boldsymbol{x} - \boldsymbol{x_0})^T A' (\boldsymbol{x} - \boldsymbol{x_0}) = 1 \qquad (2)$$

where A' is a positive-definite matrix and $\boldsymbol{x_0}$ the new center of the ellipsoid [18]. Thus an instance of the bound, closed point set $\varepsilon \in \mathcal{E}$ of an ellipsoid e is defined by the ordered pair $\varepsilon = (\boldsymbol{x_0}, A')$ that represents *spatial* and *geometrical parameter* properties. Ellipsoids of a glyph contain besides their point sets ε further *descriptive parameters* such as color *(C)*, saturation *(S)*, transparency *(T)*, opacity (*O*) and behavior *(B)* which are summarized in equation 3. This defines the complete structure of a glyph's components related to ellipsoids.

$$E = (\mathcal{E} \times C \times S \times T \times O \times B) \qquad (3)$$

An OM-glyph consists of a set of connected ellipsoids with one ellipsoid $e \in E_0$ at the center, which is in case of data being visualized without error or uncertainty properties (see [19] for details) an ellipsoid with three identical radii $r_x = r_y = r_z$ with $r_x, r_y, r_z \in \mathbf{R}^+ \setminus 0.0$ resulting in a sphere. To provide a mechanism to prevent unnecessary or insignificant data to be visualized (user controlled reduction of glyph dimension, see below), each glyph contains a filter function $\psi\colon \mathbf{R}^+ \rightarrow (\mathbf{B} \times \mathbf{R}^+)$ which prevents visualization of parameters with values remaining under a given (filter) threshold. However, if in some cases the sum of filtered parameter values is of interest, visualization can be provided by an additional ellipsoid or sphere $e \in E\psi$ being embedded in the center of the glyph. To visually improve its appearance, it is rendered with modified parameter values regarding saturation and transparency. A complete OM-glyph as shown in figure 2 is defined in equation 4.

$$G = (\psi \times E\psi \times E_0 \times (E_i \times E_m \times \ldots \times E_n)) \quad i = 1 \;\; n = max(\Theta(g)) \qquad (4)$$

The glyph dimension $\Theta\colon G \rightarrow \mathbf{N}^+$ of an OM-glyph is defined as the number of individual LC related parameter values being visualized each as an ellipsoid e_i with $i \in \mathbf{N}^+ \setminus 0$ within a glyph. For example the dimension of the glyph shown in figure 2 is $\Theta = 4$, which indicates that information about four individual LC related parameters is being explicitly visualized.

LCI Data						
Resources	**Unit**	**PreUse**	**Use**	**PostUse**	**Total**	**Use/Total**
Gross Energy Requirement	MJ	66,000	2,456,000	-	2,522,000	97%
Water	t	24	65	-	89	73%
Air emissions						
CO2 Equivalent (20 year horizon)	t	4.6	145.6	-	150.2	97%
SOx	t	0.04	1.92	-	1.96	98%
NOx	t	0.00	0.88	-	0.88	100%
Metal	kg	0.02	1.12	-	1.14	98%
Hydrogen Chloride (HCl)	kg	0.2	4.4	-	4.6	96%
Water Emissions						
Chem. Oxygen Demand (COD)	kg	0.60	1.26	-	1.86	68%
Biochem. Oxygen Demand (BOD)	kg	0.02	1.13		1.15	98%
Lead (Pb)	g	0.6	0.0	-	0.6	0%
Solid Emission						
Mineral Waste	t	0.8	1.9	-	2.7	69%
Mixed Industrial Waste	kg	30	113	-	143	79%
Slag/Ash	kg	280	515	-	795	65%
Inert Chemical Waste	kg	7.5	0.0	-	7.5	0%

Figure 1. LCI information presented in a table.

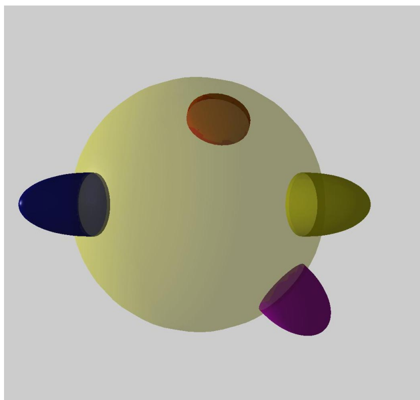


Figure 2. A rendered OM-glyph.

Note the glyph dimension Θ represents a quantitative partial measure for the amount of information being visualized within a single glyph and should not be confused with a glyph's geometrical dimension, which is linked to its visual appearance within the 3 dimensional Euclidean space.

4. Approach and examples

4.1 Outline and framework extensions

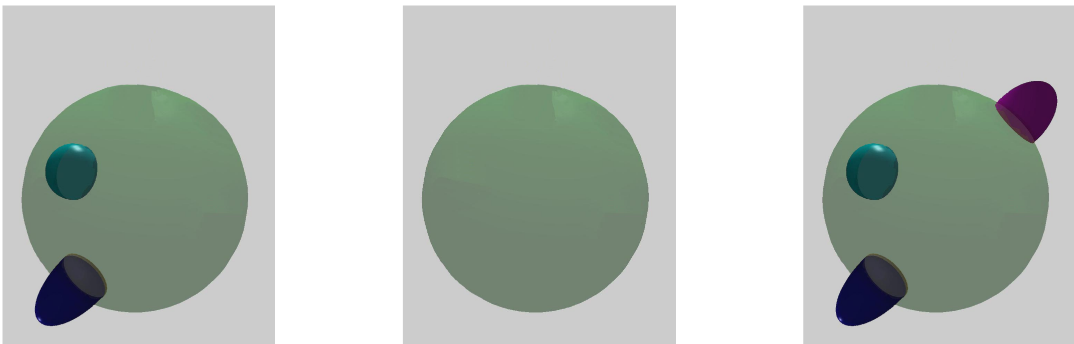
Within the novel information representation methodology to visualize life cycle related information and knowledge based on the concept of rendered interactive glyphs as introduced earlier, basic goal was to visualize LC parameter values regarding their relative and absolute contributions linked to environmental items and LC phases. This approach was aimed to provide a tool to support structural analysis of one design at a time to help experts to recognize trends, impacts and relationships among information analyzed. However, if several designs need to be analyzed and compared to either reference values or each other, the visualization framework and its functionality as introduced need to be extended. Most important in this context here is to accommodate for the proper parameter selection and computation of results, correctly reflecting such comparative design analysis, before visualization takes place. Since data stemming from a comparative analysis are structurally a little bit different from data representing LC related contributions, issues of adapting both glyph internal parameter value filtering and assignment of descriptive glyph properties need to be addressed.

First let us take a brief look at the data sets subject to visualization. During a comparative analysis individual parameters selected prior to visualization are compared to either thresholds or each other by means of arithmetic subtraction that yields one set or several sets of numerical values. Based on these values, which can be positive or negative real numbers including zero, absolute and relative differences measured in their original physical units or in percent can be calculated. Since entity values of the selection domain may now represent also results stemming from a comparative analysis, the glyph filter function needs to be extended as well to accommodate not only for negative parameters, but also for selective filtering. Adjustment of the glyph filter to accommodate for negative parameters can be achieved by exchanging the single valued filter threshold with an interval, defining the upper and lower limit, in which an individual parameter value is not qualified for visualization within a glyph. Selective filtering is required in case of a comparative analysis using thresholds for each LC related parameter value. For this analysis scenario qualitative results such as whether an individual parameter is above or below a given threshold are most important to recognize first. Thus for threshold-based analysis (see next following sections for details) parameter value computation with en suit data visualization can be efficiently realized by introducing attributes for each glyph filter threshold that are linked to parameter types. In such a case, the parameterized glyph filter function can be effectively employed as a user controlled explicit instrument for both analysis and visualization.

Representation of negative values sometimes stemming from results of multi-design based comparative analysis scenarios (see next following sections for details) requires an extension of the descriptive parameter domain of OM-glyphs. Since opacity and transparency as already introduced earlier (see also equation 3 and equation 4) are not sufficient to provide an effective means to visually distinguish a rendered ellipsoid representing a positive parameter value from a rendered ellipsoid representing the same parameter but with a negative value, texture needs to be added to the structure of OM-glyphs. Just introducing a new color for each negative value of a parameter does not represent a sophisticated approach to the problem, because it would put a heavy burden on the relationship of representing parameters with positive values and their associated color. Considering 100 or more LC related parameter values (which is quite common within complex product designs in industrial practice) associated to individual colors, this approach might not only challenge a humans capability to distinguish quickly between similar colors shown on computer displays, but would in this case also begin to compromise the basic idea of information visualization

4.2 Threshold value based comparative analysis

The analysis of LC related designs using a threshold value based approach basically provides a framework to compare parameter values of the life cycle inventory and other compiled LC related data sources to values, which at a time, are representing critical values related to certain LC phases, activities or processes. Those limit values can either be set internally by individual enterprises and industrial interest groups or being issued by governments in form of recommendations or legal limits for certain products and services. Subject to such a comparative analysis can be all types of information available such as quality, quantity and location of any entity being compared to its corresponding threshold value. In the following we will give an example of visualizing some results of such an analysis. Three different designs of one product where compared to given threshold values.



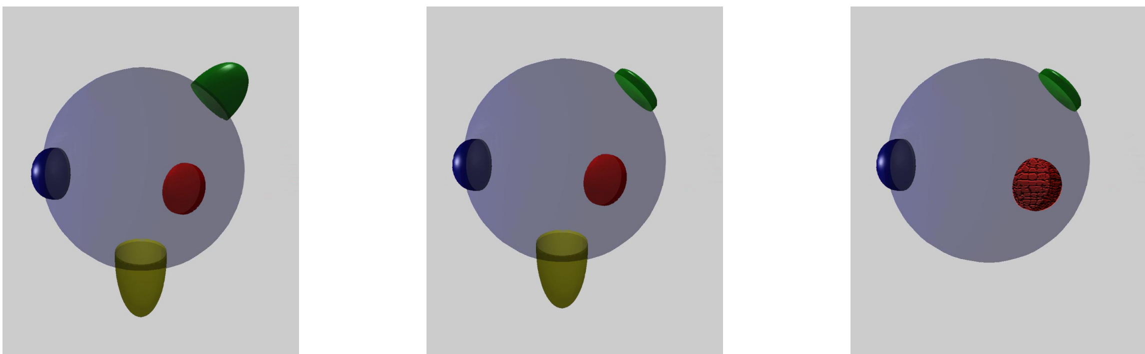
Glyph g_{m1} Glyph g_{m2} Glyph g_{m3}

Figure 3. Sequence of life cycle phase bound glyphs.

In figure 3 a section of a LC phase bound glyph sequence visualizing comparative results of environmental items is shown. The sequence shown is used to analyze the manufacturing phase (green colored spheres). Generally, a small value of the glyph dimension $\Theta(g_{mn})$ indicates that information of a design visualized within a particular glyph using threshold value based comparative analysis is with many LC related parameter values below or equal to given thresholds. This fact is visually shown by the absence of ellipsoids visualizing only contributions of LC related parameter values that are substantial enough to produce values after passing through the glyph filter. Taking again a look to the glyph sequence in figure 3 reveals immediately that the design related to glyph g_{m2} with $\Theta(g_{m2}) = 0$ contains only environmental items with contributions during manufacturing that are equal or below the threshold values given. No ellipsoids are present in this glyph excepts its sphere at the center. Glyph g_{m1} with $\Theta(g_{m1}) = 2$ (two entities have values above their related thresholds) reveals that its associated design has contributions of carbon monoxide (ellipsoid in cyan) and carbon dioxide (ellipsoid in blue) that exceed the given limits. The visualizations shown are indicating that carbon dioxide brings together about twice as much relative contribution above the limit as carbon monoxide. The design associated to glyph g_{m3} with $\Theta(g_{m3}) = 3$ (three entities have values above their related thresholds) displays similar threshold violations as the design associated to glyph g_{m1} for the environmental items carbon monoxide and carbon dioxide. Additionally contributions of dust (ellipsoid in magenta) during manufacturing exceed given limits in this design. The visualizations shown in figure 3 used a sequence of LC phase (manufacturing) bound glyphs for the analysis. This analysis scenario can be extended to include further sequences of LC phase bound glyphs for additional LC phases such as pre-manufacturing, use, or post-use, to mention only the most prominent. To acquire further explicit information about product designs regarding their weak points related to different life cycles, additional sequences of environmental item bound glyphs can be added to this analysis scenario. In this case, violations of given values of LC related parameters can be visualized explicitly for each LC phase. An example of this scenario is given in the next following section, though within the context of multi-design based comparative analysis. To obtain information on entity locations different from LC phases such as parts or assemblies within a design's product tree, which are related to threshold violations indicated within individual glyphs of a sequence, structured glyph formations such as glyph matrices or spherical glyph clusters can be used instead of single glyphs for visualization within sequences. However, due to their (spatial) complexity and printing space requirements, examples of those can not be shown here in the paper with a proper resolution, thus being only mentioned.

4.3 Muti-design based comparative analysis

The approach of multi-design based comparative analysis provides a framework for two basic (comparative) analysis scenarios. First, comparing several designs of one or several products to one design of either a reference product or an optimized product. Second, comparing several designs among each other. Depending on the goal of the analysis intending to reveal differences among designs of a product family, evaluate the evolution of a product design, gain insight of the quality and quantity of LC related differences of designs, etc. the one of these analysis scenarios most appropriate for the task shall be chosen. In the following we will give an example of visualizing some results of such an analysis using the first (comparative) analysis scenario. The section of the glyph sequence shown in figure 4 is related to three consecutively improved designs being compared to the design of one reference product.



Glyph g_{n1} Glyph g_{n2} Glyph g_{n3}

Figure 4. Sequence of environmental item bound glyphs.

The visualization scenario features environmental item bound glyphs used to analyze the contribution of carbon dioxide (blue colored spheres) within individual LC phases. Within multi-design based comparative analysis the glyph dimension $\Theta(g_{nm})$ represents an indicator of how many parameter values provide a difference considered significant or of interest. Since parameter values subject of visualization are required to pass the glyph filter first, before being rendered within a glyph, individual levels of (comparative) significance can be set by the user by providing a proper setting for the glyph filter function Θ. Now taking again a look at figure 4 the Glyph g_{n1} with $\Theta(g_{n1}) = 4$ shows significant differences of carbon dioxide contributions in all four LC phases, namely pre-manufacturing (ellipsoid in blue), manufacturing (ellipsoid in green), use (ellipsoid in red) and post-use (ellipsoid in yellow). A slightly improved design of the product related to glyph g_{n2} with $\Theta(g_{n2}) = 4$ shows similar results, though the contribution of carbon dioxide could be reduced considerably in the manufacturing phase (small ellipsoid in green). A further improved design version of the product related to glyph g_{n3} with $\Theta(g_{n3}) = 3$ and $\Theta(g_{n3}) < \Theta(g_{n2})$ shows immediately that contributions of carbon dioxide in the post-use phase could be reduced to a value considered insignificant (its parameter value difference being too small to pass the glyph filter, thus fail to be rendered as a yellow ellipsoid). Another visually easy to recognize improvement is the reduction of computed carbon dioxide contributions for the use phase. Although the (red) ellipsoid rendered within glyph g_{n3} is larger than in all other glyphs in this sequence, it displays a texture. A situation, which represents a significant negative parameter value difference, indicating that contributions of the environmental item (carbon dioxide) related to the design within the visualization analyzed are actually much lower than in the design of the reference product which it is compared to.

To further analyze product designs and their weak points related to explicit information about LC phases, additional visualization scenarios with LC phase bound glyph sequences can be used as shown earlier in the example for threshold based comparative analysis. At this point it should be noted that the representation of visualization results as shown so far, was due to the presentation form in this paper, limited to figures showing screen dumps only. In reality, those rendered glyphs are interactive 3D objects with feedback. Each glyph can be freely selected, zoomed, and rotated interactively after initial rendering is finished to suit any users visual and aesthetic needs or taste to optimize quick and efficient recognition of information visualized. Also exact, quantitative information can be provided through interactive feedback. For example, users could click on certain portions of a glyph to select from appearing pull-down menus additional data such as numerical values of contributing LC parameters or exact identifier values for certain items. Also visual highlighting of rendered negative LC parameter value differences can be realized interactively much better for example with blinking elements instead of using only texture, though problems might arise if such interactive visualizations are directly captured as screen dumps or printed on paper without taking first proper precautionary measures.

5. Conclusions

Within work presented in this paper a novel information representation methodology to visualize life cycle related information and knowledge based on the concept of rendered interactive glyphs has been introduced. Framework and structures developed and implemented were presented informally to provide for a transparent definition of basics of the methods and components used. Further developments and extensions of the information representation methodology introduced have been presented to provide additional structures and functionality, required to compute and visualize LC related information resulting from different comparative analysis scenarios of complex product designs. Unfortunately, due to limitations of allotted printing space for this paper and the sometimes quite complex geometrical and spatial nature of some glyph formations, only a small selection of computed data being visualized could be shown in the example sections. However, hopefully the benefit - regarding concentration and time required for human experts to recognize trends, impacts and relationships among information analyzed - of this advanced information representation methodology over traditional methods still using only low structured 2D numerical spread sheets, tables and charts has been conveyed.

A further enhancement of the information visualization framework introduced being currently under evaluation is the integration of an additional fourth dimension for the 3D information space, namely time. Since all essential data of LC related parameters, their computed differences within individual comparative analysis scenarios, and calculated values of all entities of each individual domain are digitally available with technology at hand to easily store and retrieve them, possibilities are within reach, to provide animated glyphs and animated glyph formations. An approach, which could provide then a first visual representation of the evolution of complex product designs that could be used as a powerful tool for design analysis while taking fully advantage of the highly developed perceptual skills and capabilities of humans for detecting spatial structures and shapes in different colors and textures.

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