Encoding Data through Experiential Material Properties

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Figure 1. [Left] An example of "Value" as implemented in 3D materials. This garment (Chen & Oliveira 2014) visualizes the users' data by varying the opacity of different parts of the garment. [Center-Left] A Galilean Thermometer, whose values are read based on the buoyancy of the liquids contained in each glass bulb. [Center-Right] Dataseeds (Gwilt & Dulake 2017) translate data into the form of a 'seed' which falls from a stairwell. The surface area and shape of the seed dictates the spin and falling speed of the object itself. [Right] Lithium chloride emits carmine light when burned.

ABSTRACT

When discussing encodings for physicalizations, visualization researchers often focus on physical properties that are persistent and clearly visible with our eyes (and occasionally reinforced through touch) including color, size, and texture. However, there are many other physical properties that impact how we perceive and interact with those materials. In this position paper, we explore opportunities for more unusual experiential properties including tactile, ephemeral, and dynamic material characteristics. We also provide both real-world and conceptual examples that illustrate how these properties can be used to encode data. Finally, we identify three opportunities for new research contributions related to experiential material properties: new types of physicalizations, new audiences for physicalizations, and new authoring tools.

Keywords: data encoding, physicalization, materiality.

1 INTRODUCTION

Current examples of physicalizations and data sculpture tend to focus on three-dimensional equivalents of graphical, two-dimensional data encodings. Two-dimensional shape corresponds to three-dimensional form; visual textures correspond to physical textures; the size of a mark corresponds to the volume of a form. However, just as the introduction of interactive media introduced new graphical visual variables, the material qualities of three-dimensional forms offer new data encodings that are unique to material objects. In this work, we draw attention to more experiential and ephemeral material properties whose potential to encode data has only been peripherally explored. We believe these alternative encodings provide opportunities for designers to create new kinds of aesthetic and embodied data-driven experiences.

Developing a comprehensive design space for data physicalization is challenging. Much of the existing expertise for information visualization comes from computer science and graphic design – domains which place little emphasis on material behavior, performance characteristics, and construction practices. Disciplines like Materials Science, Chemistry, Mechanical Engineering, and Industrial Design, meanwhile, routinely deal with a broad range of material properties. Findings from these domains can provide a deeper understanding of how material choices impact mechanical function, the challenges associated with manipulating those materials, and the semantic meanings associated with them.

"Material properties", however, is a vague term and offers an impossibly extensive scope. For the sake of this workshop paper, we primarily consider properties of **solid matter** (as opposed to liquids or gases), at or near **atmospheric temperature and pressure** conditions. We also constrain ourselves to materials that can be **formed and fabricated without unusually specialized equipment or conditions** such as extreme temperatures, high precision, or 'clean' environments.

2 BACKGROUND: INTENSIVE & EXTENSIVE PROPERTIES

When discussing material properties, it is important to distinguish where and how they apply to a particular object. *Intensive properties* are properties of the material itself, independent of how much of a material there happens to be. For example, two objects of different sizes made of the same material will (under most circumstances) appear to be the same color.

Extensive properties, on the other hand, vary based on the size or form of an object. For example, two steel objects will have different mass (kg), depending on how much material each contains. As a

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2D Visual Variables	3D Visual Variables	Examples
Size (Length, Area)	Length, Width, Height Volume Silhouette	3D Bar Chart
Shape	Form	Form Follows Data: Tableware (2009)
Value	Surface Reflectance Translucency/ Transparency	x.pose: A Wearable Dynamic Data Sculpture (Chen & Oliveira 2014)
Color	Surface Color Fluorescence	RoomQuake (Moher 2006)
Texture	Surface Roughness	Silver Ring Shaped by DNA Profile (Rezaeian & Donovan 2014)
Position	Position (x, y, z)	Plan relief map 3D Bar Chart
Orientation	Orientation (yaw, pitch, roll)	Weather Vane

Table 1. Translating 2D Visual Variables (Bertin 1983) into Visually-Apparent 3D Physical Variables

result, these properties also depend on the object's form, size, and construction, and not just it's material composition. Some intensive and extensive properties have corresponding relationships. For example, while two objects made out of the same material may have different masses (kg, extensive property), their densities (kg/m³, intensive property) will be identical.

Some extensive properties overlap with each other and are difficult to use simultaneously to encode different data values. Suppose a designer wants to create a series of objects out of the same material with the same fabrication approach, with each object encoding the annual birth and death rates of a particular countries. If the birth rate is encoded by the mass of the object (extensive), it is very difficult to simultaneously encode a death rate using volume (extensive), as these two values are linked) by the density of the material itself (density = mass/volume).

3 2D-VISUAL VARIABLES TO 3D-VISUAL VARIABLES

Most contemporary data physicalizations rely on visually apparent material properties such as material type, object volume, and surface color. Material choices, however, are generally dictated by ease of manufacture or by aesthetic choices and not used to encode data. Many of these visually apparent properties of three-dimensional objects have direct analogues to two-dimensional, graphical properties known as visual variables (Bertin 1983). We list 2D visual variables and their corresponding 3D visual variables in Table 1. Graphical size and shape translate into physical dimensions (**length**, **width**, **height**) that produce **volumes**, **forms**, or **silhouettes**. Color, value, and texture are present in various surface finish qualities including **color**, **reflectance**, and **roughness**. In some cases the visual appearance of an object is also reinforced by material properties such as **fluorescence** (the color a material emits under UV light) or a material's **translucency** or opacity.

Since the introduction of interactive media, researchers have identified additional visual variables, such as motion (Carpendale 2003). However, 'motion' is a broad category of visual variables that has yet to be deeply explored by the information visualization research community. While in digital media, dynamic behaviours are dictated by the programmer's specification, the behaviour of physical objects are constraint by the laws of physics. There are a range of material properties that can affect an object's motion. For example, an object's **coefficient of restitution** determines how it bounces off of another surface, its density determines its **buoyancy** and thus how it floats in air or water, while its **airfoil shape** affects how it moves through air. One could imagine a series of objects whose data values are apparent when they float in pool of liquid or when they fall from a stairwell (as with the Galilean Thermometer and Dataseeds in Figure 1). We list examples of these kinds of motion-influencing properties in Table 2.

Many of these 3D visual variables are still very relevant to digital 3D renderings and simulations, particularly on stereoscopic displays or in virtual reality. An accurate 3D rendering that aims to simulate how we view the physical world would thus aim to accurately re-represent these 3D visual variables virtually. However, these 3D visual variables can often be captured into a 2D medium via photography or video – the image of a 3D bar chart is, arguably, just as readable as the physical bar chart itself.

4 EXPERIENTIAL MATERIAL PROPERTIES

In the following sections, we address experiential material properties that may otherwise have difficulty being captured in a 2D medium such as a photograph or video. These include tactile properties, ephemeral properties, and dynamic properties.

4.1 Tactile Properties

Tactile properties (see Table 3) are material characteristics that can be perceived via touch. Many 3D visual variables (including size, shape, texture, position, and orientation) can also be perceived through tactile or haptic interaction. However, other material properties (particularly intensive ones) are often impossible to visually detect and rely entirely on tactile perception.

Weight and **density** are some of the simplest tactile properties to work with. While size often corresponds to weight, this is dependent on the object's material density (mass per unit volume). Moreover, perception of properties like weight depends heavily on the relationship between our initial expectations (often based on an object's size) and its actual weight once we attempt to pick it up.

Similarly, **thermal diffusivity** can also provide subtle opportunities for encoding data, leveraging our tactile perception of an object's temperature. In practice, humans are not good at judging absolute temperature; instead we are good at judging how quickly heat diffuses from a material into or away from our bodies (Tiest & Kappers 2009). Different materials have different thermal diffusivity – the rate at which the material conducts heat within itself, and thus can conduct heat away from another body, such as human skin. By creating a physicalization out of materials with different thermal diffusivities, designers could create zones or lines of material that feel "hot" or "cold", even though the entire physicalization is in thermal equilibrium and at the same temperature as the room that it is sitting in. For example, imagine that a data designer wants to create a tactile 'heat map' of real estate prices. Instead of relying on visual properties, that heat map could be made out of material with varying thermal diffusivities to communicate areas where the rental market is 'hot', or where the rental market has cooled down.

Designers could use tactile encodings, including material **stiffness**, in similar ways. For example, a real-estate map could also encode the same kinds of price variation via varying stiffness or elasticity. By tracing the physical features of a city (hills, valleys, or water features) with their hand, viewers could feel which places are expensive (the more-stiff areas that are perhaps more-difficult to purchase), and which are less-expensive (the more elastic/squishy areas that are perhaps easier to purchase).

Motion Influencing Property	I/E	What is it?
Coefficient of Restitution	I	How 'bouncy' an object is; how much kinetic energy is retained when it bounces against another surface
Buoyancy	E	Upward force on an object when submerged in water.
Airfoil Shape	E	Shape of a wing or blade, which dictates how an object moves through a fluid and produces aerodynamic force.

Table 2. Motion-influencing properties and their definitions, including whether the property is (I)ntensive or (E)xtensive.

Tactile Property	I/E	What is it?
Weight (N)	E	The amount of force acting on an object due to the acceleration of the earth's gravity
Density (kg/m³)	I	The mass per unit volume of a particular type of material.
Thermal Diffusivity	I	How quickly heat transfers within a material from the hot side to the cold side. Calculated based on the thermal conductivity and the volumetric heat capacity.
Stiffness	E	How much material resists deformation in response to an applied force

Table 3. Tactile Properties and their definitions, including whether the property is (I)ntensive or (E)xtensive.

Ephemeral Property	I/E	What is it?
Pyrotechnic Color	I	Color of light emitted by a material/metal when burned.
Tensile Strength	E	How much stress a material can withstand in tension before breaking .

Table 4. Ephemeral Data properties and their definitions, including whether the property is (I)ntensive or (E)xtensive.

Dynamic Properties	I/E	What is it?
Electrical Resistance	I	How much electrical energy is dissipated when current passes through the material.
Thermal Expansion	I	Describes how much the size of an object changes (expansion or contraction) in response to a temperature change

Table 5. Dynamic properties and their definitions, including whether the property is (I)ntensive or (E)xtensive.

Many of these tactile properties are active areas of research in related fields including human perception, thermal or haptic displays, and VR haptic output technologies.

4.2 Ephemeral Properties

In the physical world, materials decay. While some kinds of material decay proceed so slowly that they are essentially invisible at human time scales, other forms of material destruction occurs at rates that are readily observable. For example, some materials when burned produce wavelengths of light that fall on the visible color spectrum (see Figure 1) – a phenomenon known as **pyrotechnic color**. Using this property, a physicalizations designer could create a fireworks show where the color of the fireworks (the color emitted by the material of the fireworks when combusted) encodes categories or values from a data set.

Other properties emerge when faced with more mechanical forms of destruction. Suppose a designer wanted to represent the strength or weakness of people's immune systems using the **tensile strength** of different materials. Tensile strength – the extent to which it plastically deforms under load – is not truly apparent until a material is loaded with enough force for it to deform, well on its way to destructive failure.

Manual fabrication using materials with varying tensile strength, toughness, or pliability could also offer a data-driven experience. For example, a data designer could create an installation with a set of wires, the length of each wire representing military spending in a different country. The material of each wire could respond differently to the process of being bent – some materials are easily pliable, while others are pliable but require more effort as the material continues to bend, and still others are brittle and fracture. In the installation, visitors could bend wire into the shape of its corresponding country – and the material response would communicate the popular support for military spending within that country. Countries whose citizens are in favor of military spending would bend easily; countries whose citizens are more hesitant might bend but require more force; countries that do not have popular support for military spending might be made of brittle material that cannot be deformed without fracturing.

If encoding with such destructive properties, the resulting data representations would be more performative or ephemeral. And, perhaps, more memorable thanks to our visceral reaction to material destruction (Eickhoff et al. 2016).

4.3 Static and Dynamic Properties

Many physicalizations are static data sculptures – consistent forms that are not fundamentally varying, kinetic or shape-changing. However, a dynamic physicalization can dynamically vary the values that it represents over time. To create dynamic physicalizations, the designer needs to be able to actively control physical properties. The most obvious category of material properties that respond to control are electrical or magnetic. For example, a physicalization can use microcontrollers to vary the amount of current, create a voltage difference, or send an electrical signal that can alter some physical properties in response to data. Dynamic visualizations can also leverage a combination of physical properties to produce a visual or material change. For example, materials with greater **electrical resistance** often become hotter as current runs through them, and many materials exhibit **thermal expansion** as their temperature changes. A classic example of this is shape-memory wire which, after being deformed, returns to its original shape when heated. When electrical current is run through the wire, electrical energy is dissipated as heat in the wire, initiating a physical change in the shape of the material. There are other examples where manipulating the temperature of a material corresponds to a physical change in the material's properties. A

simple example of this is a balloon – on a hot day, the gas inside of the balloon will increase in volume; on a cold day a balloon will shrink in volume.

5   RESEARCH OPPORTUNITIES

How do these experiential material properties ultimately relate to physicalizations research? These experiential properties expand the design space of physicalizations by going beyond 3D visual variables. These alternative physicalization genres highlight *new ways to experience data* physicalization and suggest *new audiences* for physicalizations and *new tools for designing and authoring* physicalizations.

5.1   New Physicalizations

By going beyond visually apparent physical material qualities, data designers can use this palette of material properties to design a variety of new ways to 'experience' data. As illustrated by our conceptual examples, these alternative properties offer new ways for a designer to not only communicate data, but to build on semantic associations those properties embody. (For example, mapping high real estate prices to materials that are more difficult to physically deform could signal that those homes might be more difficult to purchase.) While unconventional, these material properties expand the range of possible materials or encodings that a designer might consider when creating a representation.

5.2   New Audiences

An expanded design space of physicalizations also has the potential to reach new audiences who are not necessarily served by more 'traditional' physicalizations, which are still deeply grounded in 2D visualization practices. Moreover, tactile and dynamic properties have the potential to increase the accessibility of physicalization to people with visual impairments. Similarly, kinesthetic learners (Begel et al. 2004) may better comprehend or engage with data when presented with a mechanical behavior than a visual image.

5.3   New Design and Authoring Tools

While engineers and industrial designers currently handle materials selection decisions as part of their everyday practice, many of these decisions are made for functional or aesthetic reasons. Data designers need to not only consider aesthetics and manufacturability, but also the semantics of how different materials and their properties will convey data and their relative strengths and limitations as data encodings. There is a need for new design and authoring tools that help designers develop and prototype both material properties and how they might affect a resulting physicalization. Just as graphic designers refer to pantone books to specify colors, many materials companies offer physical samples to help mechanical engineers and industrial designers decide on the right material for a particular project. Future research could explore how materials samples could help data physicalization designers explore new ideas – particularly those that involve experiential material properties.

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