PRINTING THE INVISIBLE
Bridging the Gap between Data and Matter through Voxel-based 3D printing

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Submitted to the
PROGRAM IN MEDIA ARTS AND SCIENCES,
SCHOOL OF ARCHITECTURE AND PLANNING,
in partial fulfillment of the requirement for degree of

MASTER OF SCIENCE IN MEDIA ARTS AND SCIENCES
at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY
June 2017

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ABSTRACT
Scientific visualizations are central to the representation and communication of data in ways that are at once efficient and effective. Numerous data types have established unique formats of representation. In the context of three-dimensional (3D) data sets, such information is often presented as a 3D rendering, a video or an interactive application. The purpose of such visualization is often to emulate the physical, three-dimensional world; however, they remain inherently virtual.

Recent advancements in additive manufacturing are making it possible to 'physicalize' three-dimensional data through 3D printing. Still, most 3D printing methods are geared towards single material printing workflows devoid of the ability to physically visualize volumetric data with high fidelity matching their virtual origin. As a result, information and detail are compromised.

To overcome this limitation, I propose, design and evaluate a workflow to 'physicalize' such data through multi-material 3D printing. The thesis focuses on methods for voxel-based additive fabrication at high spatial resolution of three-dimensional data sets including – but not limited to – point clouds, volumes, lines and graphs, and image stacks. This is achieved while maintaining the original data with high fidelity. I demonstrate that various data sets – often visualized through rasterization on screen – can be translated into physical, materially heterogeneous objects, by means of multi-material, voxel-based 3D printing. This workflow – its related tools, techniques and technologies contained herein – enables bridging the gap between digital information presentation and physical material composition. Developed methods are experimentally tested with various data – across scales, disciplines and problem contexts – including application domains such as biomedicine, physics and archeology.

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1 INTRODUCTION

The visualization of information is deeply interwoven in human culture and is an ubiquitous part of our daily life, as it supports our need to communicate, educate and learn. Especially in the scientific research context, visualization is a crucial task that supports the process of analyzing and understanding data and from that, conveying newly created information. In many cases, scientific data captures information from the physical world, which means that data has to be observed in a spatial context. This visualization task is mainly achieved through screen-based media, for example, in the context of radiology, volumetric rendering of patient data obtained from MRI, or in the context of geographic information systems, point-based rendering of geospatial data obtained through aerial laser scanning. Research in the field of computer graphics constantly pushes the technology ahead that tries to emulate the virtual world, for example, virtual reality hardware that is becoming more and more popular in recent years. But since these visualization methods are always virtual, there are other strategies that attempt to transform three-dimensional data back into physical, tangible objects. The accessibility and affordability of digital fabrication workflows and tools – such as additive manufacturing – have enabled an uprising in the production of physical manifestations of data. Consequently, the representation of data sets in physical form through digital fabrication has emerged as a research area and practice [1]. More broadly, these and similar methods of bringing data to a physical form are often collected under the term data physicalization [2] or physical visualizations [3]. The fundamental idea is to map data to properties of a physical object.

There exists a wide array of tools and frameworks for digital, screen-based visualizations, ranging from interactive web frameworks, to high-end animation software and game-engines that are accelerated by powerful graphics hardware (Figure 1). But for the fabrication of tangible data objects, there are only a few workflows that are often tied to a particular type of data or format of presentation. Furthermore, the resolution and level of detail with commonly used additive manufacturing processes, laser cutters and CNC routers are enough for certain use cases, for example, 3D bar charts or elevation maps. These fabrication tools, however, limit the precise reproduction of high-resolution data sets, as are commonly found in scientific visualizations. Volumetric information, specifically, cannot be physically reproduced without the loss of visual fidelity, and consequently, information. In
additive manufacturing, multi-material 3D printers, are a particularly valuable tool to fabricate tangible visualizations, as they provide high degree of freedom regarding shape, color and material. Unfortunately, common design workflows for such printers can be very limiting, despite their powerful hardware. To overcome this obstacle, I propose a workflow and method to additively manufacture three-dimensional data sets through multi-material, voxel-based 3D printing, which transfers on-screen pixels to material droplets. The results are tangible objects that closely resemble the screen-based visualizations from which they originate. This approach enables the ability to bridge the gap between digital data representation and physical material composition. Many data sets, which can be visualized on screen through rasterization, can be directly 3D printed through this workflow, overcoming the need of any intermediate data representations, as are usually required with current 3D printing workflows.

Figure 1: Example of state of the art screen-based scientific visualization [4]. Cinematic Rendering application by Siemens Healthcare, that allows for the fast and realistic rendering of volumetric data through GPU accelerated Monte-Carlo path tracing methods [5]. Copyright: radiologie im Israelitischen Krankenhaus, Hamburg, Germany.
2 BACKGROUND

My research area lies at the intersection of information visualization/scientific visualization, data physicalisation and digital fabrication/additive manufacturing. The following section will provide an introduction to those topics and offers a way by which to link them to the proposed work.

2.1 Information Visualization/Scientific Visualization

Information visualization and scientific visualization are closely related: both fields utilize computer-aided representation and analysis of data to enable and reinforce human cognition. The main difference between the two is the data source on which they operate. Information visualization operates on non-physical data, whereas scientific visualization operates on data captured from physically based phenomena [6]. Figure 2 provides examples of both cases, suitable to be produced with my proposed approach as per below.

![Figure 2: (a) Information visualization: graph that maps parts of the network nodes of the internet. Lines represent the connection between two IP addresses, where the line length encodes the delay between nodes. (b) Scientific visualization: interactive volumetric rendering of a hand captured through CT scanning.]
2.2 Data Physicalization

'A data physicalization (or simply physicalization) is a physical artifact whose geometry or material properties encode data.' [2] There is a community of artists, designer and scientists that address the question of how to visualize data through tangible objects. The diversity of data physicalizations is high, ranging from abstract pieces of art that allow for interpretation and speculation [8], to 3-dimensional graphs that are designed to enhance the comprehension and perception of data sets [9][1][3], or scientific visualizations like anatomical models that try to precisely replicate captured data to assist in the pre-surgical planning process [10].

Popular examples of tangible visualization are data sculptures that encode information in an artistic way by using data to drive object properties like shape or color. Such sculptures engage people by telling a story through a data embodiment that is often times visually engaging and thought provoking. Data sculptures range from jewelry that visualizes the communication flow of a long distance relationship to small artifacts that encode the worldwide occurrence of nuclear detonations and museum installations like the walkable age pyramid that illustrates the distribution of age groups after the Second World War [17].

The aforementioned data sculptures could all be summarized as static data physicalizations, as they show a data set in one specific state at a specific point in time. One advantage of screen-based visualizations is their high degree of interactivity by reacting and responding to user input. To leverage the interactivity in physical visualizations, there are tools and projects such as constantly adapting, dynamic data physicalizations [11] or tangible interfaces that respond to user input [12]. My proposed workflow and approach will be geared towards the creation of static data physicalizations, especially scientific visualizations based on high resolution data sets that can’t be accurately replicated through other digital fabrication processes.
Figure 3: Examples of 3D data visualizations. (a) Artistic data sculpture by Nathalie Miebach, that looks at the meteorological and oceanic interactions within the Gulf of Maine [13]. (b) Three-dimensional bar chart that was created with the MakerVis software [14]. (c) 3D printed, anatomical heart model from the rapid prototyping company Materialize [10]. (d) Jewelry by Paul Heinicker that encodes the chat history of a long distance relationship [15]. (e) Data sculpture by Scott Kildall that encode the worldwide occurrence of nuclear detonations [16]. (f) Data sculpture by Atelier Brueckner that illustrates the distribution of age groups in Germany between 1950 and 2010 [17].
2.3 Digital Fabrication/Additive Manufacturing

Digital Fabrication denotes the joined process of computer aided design in combination with subtractive and additive manufacturing. Subtractive manufacturing describes the superset of machining processes like drilling, turning, grinding, laser cutting, CNC routing, etc. Whereas additive manufacturing describes the superset of 3D printing processes like Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), Stereolithography (SLA), Polyjet, etc. Most data physicalizations are produced through digital fabrication, where the data is used in the design process to drive the manufacturing process. The results are data embodiments that, depending on the used design and manufacturing process, can resemble the original data closely or in a more abstract way.

One example in the domain of subtractive manufacturing is a framework called MakerVis [1] from the Visual Analytics Project [14] of the french INRA. The software is designed to enable a simplified digital fabrication workflow for the production of three-dimensional graphs (scatterplot, prism map, bar chart, etc.) through laser cutting and manual assembly. The software takes input data and creates a construction plan for a specific type of graph. The construction plan includes a machining tool path for a laser cutter, which produces flat wooden or acrylic shapes that are manually assembled to create the three-dimensional, tangible visualization. As the framework allows for the quick and easy production of data physicalizations at desktop scale, it also illustrates the limitations of this fabrication process. The framework enables only the fabrication of specific data sets and introduces several intermediate production and abstraction steps that transfer the original data into a tangible object with a rather coarse resolution compared to what is possible with screen-based rendering. Furthermore, volumetric data sets, specifically, can’t be produced with such fabrication processes, without the loss of great detail and information.
One fabrication method in the realm of subtractive manufacturing, that is capable of producing higher resolution, three-dimensional data is 3D laser engraving [19] also known as *vitrography*. This method uses a laser that engraves digital, 3D objects inside a glass or polycarbonate cube. The laser focuses inside the cubic media, where it introduces damage to the material in form of small dots. When viewed under daylight the damaged areas produce light refraction and scattering, which results in the appearance of little white dots, that form a surface or volume. Though this technique is mainly used for the production of souvenirs and advertising media, its use for the production of scientific visualisations has been demonstrated, as shown in Figure 5. One advantage of this fabrication method is the possibility to produce relatively detailed and disconnected data sets, that appear like they are floating in space, similar to screen-based visualization. Furthermore, since the visualization is embedded within a single material cube, the data object is durable and tough. Yet, this method also comes with limitations, particularly the lack of color, lack of varying volumetric transparency and freedom of an arbitrary enclosing shape.
There is yet another fabrication process, that has a similar volumetric look than 3D laser engraving and additionally introduces color. The process is a combination of subtractive and additive manufacturing. Slices of a digital 3D model are generated and 2d printed on thin acrylic sheets, that are cut out and assembled in a stack. The slice stack is submerged in a refractive index-matching fluid, that reduces light scattering between the sheets, inside a cuboid enclosure that is vacuum sealed. The results are fully colored, volumetric visualizations that overcome some limitations of the 3D crystal engraving process described above. However, at the same time, this process introduces new drawbacks. Similar to vitography the visualizations are constrained to a cuboid container. The 3D laser engraving results in a materially homogenous object, whereas this fabrication process is more involved and results in more fragile composite object, that is for example prone to leaking of the index-matching fluid. Furthermore the resolution in the direction perpendicular to each slice is much lower then the resolution inside the slice image, as this resolution is limited by the height of the used acrylic sheets. The described process is illustrated in Figure 6 and was introduced through a Kickstarter campaign [20] by New York based company Looking Glass Factory [21] that named such objects Hologram 2.0. The production of these data objects is discontinued, as the company now focuses on holographic displays.
Figure 6: *Hologram 2.0* [20] by *Looking Glass Factory*[21]. (a) 2D slices of a 3D model are 2d printed onto acrylic sheets. (b) The slices are stacked and submerged in a refractive index-matching fluid inside a vacuum sealed container. (c) and (d) The result are three-dimensional visualizations of volumetric data.

In many cases, subtractive manufacturing requires a significant amount of individual steps, including machining, post-processing and assembly, that transform several individual parts into one single object. Additive manufacturing (AM) on the other hand enables the efficient and rapid production of unique parts with intricate shapes in a single manufacturing process. Moreover, physical data visualizations are individual items, which use shape and color as primary parameters to encode information. Therefore additive manufacturing is an ideal tool for the fabrication of sophisticated data embodiments, where each object is as unique as the data from which it originates.
Figure 7: Tangible models produced through various 3D printing technologies. (a) White matter brain tractography data fabricated through Selective Laser Sintering.[22] (b) 'Crystalized' visualization of data from the Facebook API, fabricated through Binder-Jetting 3D printing.[23] (c) Shoe prototype produced through PolyJet 3D printing, incorporating several flexible, colored materials.[24]

Figure 7 shows several examples of different AM methods and their usage in the context of data physicalization. Figure 7 (a) visualizes white matter tractography data of a human brain, that is manufactured via Selective Laser Sintering (SLS). This AM method works with a laser, that constantly solidifies a fine, granular substrate layer by layer. SLS is only capable of producing 3D prints in a single material in one opaque color, which limits the encoding parameters of a physical visualization to just shape. However as SLS, in contrast to FDM or SLA, does not require support structures and is capable of producing intricate details and an uniform smooth surface finish, it is commonly used for the production of detailed data embodiments.

To use color as a second encoding parameter an AM method called Binder-Jetting is commonly used (Figure 7 (b)). The method works by jetting colored binder into a granular substrate, which solidifies the material layer by layer. Through this method, it is possible to create fully colored, opaque 3D prints that are more fragile than SLS prints, but also omit the use of dedicated support
structures and material. This makes this method popular for the production of colored data physicalizations.

Figure 7 (c) shows the 3D print of a product prototype, which was produced with an additive manufacturing method called PolyJet. This process fabricates tangible objects by jetting colored, photo-curable resin layer by layer, which is cross-linked with UV light. This approach is especially powerful as it enables the deposition of multiple colored and transparent materials in a 32 micron resolution in three dimensions. As a result, this AM method is specifically useful for the production of physical visualizations, as it enables the greatest possible freedom regarding shape, color and material compared to other additive manufacturing processes. Despite the availability of powerful hardware, currently available 3D printing workflows and software do not make use of this capability. Therefore, in the following chapters, I will demonstrate methods to harness the full potential of the PolyJet technology through multi-material voxel-based 3D printing.
3 PROBLEM & APPROACH

3.1 Problem Statement

As seen in the data sculpture examples in chapter 2, physical data visualizations can be very artistic and present information in an abstract way. However, in the case of scientific visualizations, it is often intended to accurately represent the full extent of information available in a data set. Especially in cases when data physicalizations are used to support a data analysis process, the tangible object should closely resemble the data from which it originates. Therefore, it is desireable that a chosen digital fabrication process does not introduce additional abstraction or alteration of the original information. For example, a digital 3D model, which is represented through a polygon mesh, could be reproduced through a digital fabrication process that outputs a *waffle model*, by creating horizontal and vertical contours of the digital model, which are laser cut into 2D sheets and assembled. But such a process would always compromise information and represent the digital model in an abstracted way, as the process alters the original data in order to make it compatible with the fabrication process.

To date, additive manufacturing (AM) is considered state-of-the-art for the precise production of objects with intricate shapes, which, as discussed above, makes it particularly useful for the production of scientific data embodiments. The technology dates back to the 1980s, where it originated from industrial rapid prototyping and tool making. Recently, new companies have emerged that advance the availability of affordable AM technology, ranging from printer hardware, materials and software. As a result, AM is becoming more widely available to industries, academic institutions, and the general public. Despite the rapid development of AM technology, fundamental 3D printing workflows have remained essentially unchanged for the past 30 years. These workflows are limited by the fact that shape-specification is directly linked with material-specification. This limitation is also reflected in the STL file format, which was specified 3 decades ago for the first stereolithographic 3D printers and is still considered the standard file format for additive manufacturing.

The STL file format represents objects through a closed 2-manifold, which is described as a list of triangles, defined through vertices [25]. During the 3D printing process each STL file is...
considered a solid object, where space inside the triangle boundary representation will be occupied by a single material. Unfortunately, these design and additive manufacturing workflows don't think 'beyond the shell' of objects, despite the fact that commercially available 3D printers can print up to 7 materials simultaneously. This means, in order to 3D print any data set, first all data has to be converted into a boundary representation. Specifically for scientific data, this conversion process is problematic as for many cases it introduces computational overhead, alteration of data and even loss of information.

Figure 8: White matter tractography data [26], created with the 3D Slicer medical image processing platform [27]. The whole data set consists of 5721 fibers represented as polygon chains. (a)(b) The fiber data is represented as lines consisting of 625,078 vertices. (c)(d) In order to prepare the data set for conventional 3D printing processes, the fibers are converted into tubes that are now represented through a total of 6,250,780 vertices, which is an increase of the vertex count by a factor of 10.

Figure 8 illustrates the conversion process of white matter tractography data of a human brain. The fiber data that is rendered on screen is represented through 5721 individual colored polygon chains with a total of 625,078 vertices. In order to 3D print this data set, a 3D strut algorithm can be used that creates a tubular enclosure for every polygon chain. The resulting STL file is represented though
6,250,780 vertices, which increases the vertex count of the new data set by a factor of 10, compared to original file. Furthermore the color information that is stored in the newly created strut structure can’t be directly imported into the printing software of modern multi-material 3D printers. A workaround for this problem is the use of an additional color texture that some of the printer software can read. But regarding the size of the strut file, the process of texture mapping and transferring vertex colors to a dedicated texture map is inconvenient and creates further overhead.

Figure 9: Image stack that captures data observed through protein-retention expansion microscopy [28]. (a) and (b) show one slice of the image stack and a magnification thereof, that demonstrate the high level of detail stored in the data set. (c) shows an ISO-surface created from the whole image stack. As seen in magnification of the data set (d), it is difficult to represent the information from the image stack as a 3D ISO-surface, because due to the nature of the conversion process, volumetric information and detail is lost.

Figure 9 shows another example of a scientific data set that is particularly difficult to additively manufacture with common 3D printing workflows. The data represents volumetric information in the form of an image stack that is captured through protein-retention expansion microscopy [28]. One possible workflow of additively manufacturing such data would for example require to initially convert the image stack into a three-dimensional volumetric data structure, where every image pixel
is mapped to a volume voxel. Since each image of the stack has a resolution of 2316px * 1901px, the resulting volume with a height of 460px consists of 2 billion voxels, which makes any processing on this high resolution data set computationally intensive or even impossible. The next step would involve the generation of an STL file through ISO-surface extraction based on a specific range of intensity values from the defined volume. Figure 9 (c) illustrates this approach, which also highlights the difficulties associated with this method. In this example, the ISO-surface had to be created from a lower density volume than the original data set, since the original data resolution was too high to extract a surface in an acceptable time frame. Yet, the resulting surface description consists of about 1 million polygons that fail to capture the fine details of the original file. Furthermore, due to the thresholding process during ISO-surface extraction, any volumetric information including transparency and color gradients are lost. Through the conversion process, the initial volumetric information is compromised and the generated model does preserve the original internal volumetric details.

The STL files, created by the two examples above, would then be further processed by the 3D printer software, which slices the incoming STL files, determines the inside of objects and creates material deposition instructions for the printer hardware. Overall, the described conversion workflows result in computational overhead and alter the original data in a way that can generate discrepancies between the virtual and the physical visualization.

3.2 Approach

To overcome the herein described limitations associated with common 3D printing workflows, I introduce a data-driven material-modeling framework that is targeted at multi-material additive manufacturing. In addition, I present specific methods, which are implemented in the framework to fabricate data sets that are commonly used for scientific visualization, which will enable a unified workflow to directly manufacture scientific data sets, without compromising accuracy and visual fidelity.
Figure 10 illustrates the common additive manufacturing workflow: Boundary surface files like STL, OBJ, COLLADA, VRML, X3D, etc. are used as a common denominator to transform digital data sets into a 3D printable representation. The transformation process usually involves data-specific surface reconstruction methods, that are either implemented as export functions in common CAD or visualization software, or that are available as specialized stand-alone applications, like for example, medical segmentation software. The surface files are merged in the printer software, where properties like color and material information are specified and then translated into a printer readable format.

Figure 10: Common additive manufacturing workflow, where input data undergoes data set-specific transformation steps, in usually several software frameworks to translate the original information into a 3D printable representation.

Figure 11 shows the idea of a data fabrication framework that shall enable a unified approach to translate scientific data sets into a 3D printable description. Instead of treating every data set individually, input data is processed with a unified, fabrication specific rasterization process, which omits any unnecessary intermediate conversion steps, thereby reducing computational overhead and data alteration during data processing.
Figure 11: Data fabrication framework omitting any unnecessary intermediate conversion steps, reducing computational overhead and data alteration during data processing.

The framework and methods presented herein are implemented with the PolyJet [29] 3D printing technology, using the Voxel-Print interface. As with most additive manufacturing systems, PolyJet is a layer-based process. This AM method works by precisely jetting multiple photo-curable resins at once, layer-by-layer, building up a three-dimensional material volume. The VoxelPrint interface enables the user to bypass the standard printer software and to interface with the 3D printer directly, which enables control over material deposition on the droplet level. PolyJet hardware allows printing at a droplet resolution of 300 dpi, which is also the resolution commonly used for (2D) printed materials (photographs, maps, etc.). Printed ink or resin dots that are observed in a comfortable viewing distance at this resolution, do no longer appear as distinct entities, but are rather observed as a homogeneous area or volume. This enables the production of objects that have a similar visual quality as media that we observe in print or on screen.

The hardware capabilities, in combination with the ability to address every single material voxel in the printer’s build volume, led to the idea to use the 3D printer as a render target for the visualization of scientific data sets. The fundamental idea is to use known computer graphics rendering methods and apply them to calculate the printer’s material deposition descriptions, which are specified in a raster file format. This effectively enables to bridge the gap between digital data representation and physical material composition, which results in physical visualizations that have a high similarity with digital visualizations rasterized on screen.
In the following, two case studies are presented. The first, entitled "Data-Driven Material Modeling with Functional Advection for 3D printing of Materially Heterogeneous Objects" introduces the data-driven fabrication framework and provides an overview of a multi-material modeling approach that is designed with versatility and scalability in mind. A key concept is the introduction of a framework, for the computation of the printer's material deposition descriptions, that decouples internal material specification from the outer shape of objects. This enables the fabrication of materially heterogeneous artifacts with continuously varying material properties. Modern multi-material printer offer build volumes up to 40,000cm³ resulting in over 370 billion individually addressable material voxels. Such large volumes can’t be stored in memory at once, which makes the design process and the pre-computation of material compositions of large 3D printed parts difficult.

The 3D printer deposits material in a layer-by-layer process and therefore requires per-layer material deposition descriptions. As a result, material computation is deferred to the time of print layer creation, which allows specifying material compositions at the native printer resolution, which in turn enables essentially unlimited scalability of the framework. This approach was demonstrated in an artistic computational design context. Several computationally generated data sets are created, which inform the material composition of the designed artifact. In this particular example, functional advection of the material volume is used to create realistic, fluid-like patterns.

The second example, entitled "Voxel-Printing for Data Fabrication" specifically demonstrates the implementation of rasterization processes, which are designed for the data-driven fabrication of physical visualizations based on point clouds, volumes, line & graph data, and image-based data sets. Moreover, the visual characteristics of the multi-material modeling process is described in detail, including the fabrication of minimum feature sizes of primitive shapes and material translucency when mixing transparent and opaque resin. Each chapter features common data sets and showcases the results when fabricated with the herein presented framework and methods. This shall enable the additive manufacturing of data sets in a quality similar to screen-based visualizations.
4 DATA-DRIVEN MATERIAL MODELING WITH FUNCTIONAL ADVECTION FOR 3D PRINTING OF MATERIALLY HETEROGENEOUS OBJECTS

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Published in Journal of 3D printing and Additive Manufacturing, Volume 3, number 2, 2016, pp. 71-79

4.1 Abstract

We present a data-driven approach for the creation of high-resolution, geometrically complex and materially heterogeneous 3D printed objects at product scale. Entitled Data-driven Material Modeling (DdMM), this approach utilizes external and user-generated data sets for the evaluation of heterogeneous material distributions during slice generation; thereby enabling the production of voxel-matrices describing material-distributions for bitmap printing at the 3D printer’s native voxel resolution. A bitmap-slicing framework designed to inform material property distribution in concert with slice generation is demonstrated. In contrast to existing approaches, this framework emphasizes the ability to integrate multiple geometry-based data sources to achieve high levels of control for application in a wide variety of design scenarios. As a proof of concept, we present a case study for DdMM using functional advection, and demonstrate how multiple data sources used by the slicing framework are implemented to control material property distributions.
4.2 Introduction

Recent advances in high-resolution 3D printing have enabled the design and digital fabrication of objects with unprecedented levels of structural complexity [30][31]. However, while most commonly implemented methods for the production of 3D printable file formats rely on the generation of highly detailed surface meshes and object assemblies, they often neglect to address, or overlook, the functional need and design potential of heterogeneous material distributions that are volumetric in nature, and which take full advantage of the native resolution of a 3D printer.

Modern multi-material 3D printers [29] employ photo-polymerization of UV curable resins to construct 3D objects through an inkjet-like printing process by sequentially depositing layers as thin as 32 microns. This high-resolution 3D printing approach enables precise spatial control over the deposition of individual material droplets, where material composition is controlled at the droplet level by defining – for each deposited material – a binary 3D voxel matrix at the native resolution of the printer. This voxel-matrix, in turn, defines the material identity of the individual droplets and their spatial placement in space, resulting in volumetric binary material representations that can be used to define heterogeneous and continuously varying material composites at the resolution of the printer. This approach is often described as bitmap-based printing or voxel-printing [32].

Design approaches that rely solely on voxel-based representations [33][34] for 3D multi-material compositions are often challenging to scale for the production of high resolution, large volume models. Since commercial multi-material 3D printers can offer build envelopes as large as 40,000 cm³; defining binary 3D matrices at the native resolution of the printer, results in billions of individually addressable voxels, whose representations can become overbearing in size and challenging to handle.

In the following section, we present a data-driven design approach for the production of a materially heterogeneous object, printed on a multi-material 3D printer. We showcase a Data-driven Material Modeling (DdMM) approach in the form of a case study named *Lazarus*. In contrast to previous design approaches, this approach allows us to specify multiple generated data sets, which are used to inform material distributions during slice generation. Furthermore, *by partially reallocating data-transfer and data-modification to occur at the time of individual slice generation, we show how*
bitmap-printing in combination with function-driven material advection can be used for the design of highly complex and intricate material distributions. Additionally, by employing a custom system for the direct input of bitmap-slices to control a 3D printer, this workflow, thus allows us to fully leverage the native resolution of the 3D printer for large scale objects, highlighting the versatility, scalability, and usability of high-resolution bitmap-printing for design and engineering applications.

4.3 Data-driven Material Modeling (DdMM)

4.3.1 Computational framework

To facilitate the use of external data-sources for the design of internal material distributions, and building on previous methods [35][36][37], our approach accounts for arbitrary external geometric data sets such as point-clouds, scalar and vector fields, curves and polygons, tetrahedral meshes, with their associated attributes, as shown in the case-study below. Using these external data sources, it is possible to drive the computation of hybrid evaluated and unevaluated heterogeneous material modelling methods [38] including distance-based [39], source-based [40], or synthesis-based [41] approaches during slice generation for 3D-bitmap-printing. As such, this approach is designed to handle data-sources and to generate material-distributions during slice generation (on-slice-time) and, therefore, it permits the incorporation of external data as the primary design element in the creative process for multi-material 3D-printed objects. Despite these significant advantages, it should be noted, however, that only computational modifications to provided data-sets can be used with this approach for which either sufficient data can be pre-computed and provided during slicing, or which allow neighborhood-limited evaluation of material-distributions. An overview of this workflow is provided in Figure 12.
Our framework uses polygonal meshes, with user-defined material domains as source files. Each mesh is then sliced in the print-direction, resulting in a set of rasterized layers where each pixel/voxel can store, for example, material information, vectors for velocity fields, matrices, or other data structures. The resulting rasterized content is then dithered into $n$ binary bitmaps providing instructions for the material deposition of $n$ materials as defined by the printer. Furthermore, as mentioned above, we can integrate external geometry-based or user-generated data-sources of arbitrary dimensionality, which can then be used to influence the generation of the 3D-printable description at any stage of the description generation process. Figure 12 (a) shows the object-representation and data-generation stages, where each object is indexed to a material-computation domain and additional data-sources can be computed and assigned for later use – for example – as part of the on-slice-time material generation step. We note that, while material-computation domains are discrete, their internal material-distributions can be continuous and heterogeneous. Figure 12 (b)-(e) illustrates the rasterization of a bitmap slice obtained from a polygonal object, where we treat the generation of a polygonal slice as an optional stage. Figure 12 (c) shows a priority-ordering step, describing, in a fully user-controlled manner, which material-domain has higher precedence. This approach is required in cases where two or more geometric material domains are overlapping, and, as a result, a defined
priority has to dictate which material will be deposited. An example of data-driven priority-ordering is shown in Figure 13.

Figure 13 An example of data-driven priority sorting for the production of large and structurally complex objects [42]. In this example, the design consists of 15,543 polygonal tubes, curled and aligned to a predefined surface contour, which are encapsulated in a 41.2 by 30.5 by 16.7 cm hull. Every tube can be assigned a uniquely different longitudinal material gradient and priority data is given by the distance from the surface contour. (a) A layering priority is assigned to each vertex of the polygonal tube according to its desired visibility in the final form, which varies as a function of distance from the underlying surface; (b) The design is aligned to the build-tray of the printer; (c) A slice is generated; (d) Visualization of the priority sorted segments of the design in the z-direction before rasterization; (e) Resulting 3D printed model. Photo: Yoram Reshef, courtesy of Mediated Matter.

Figure 12 (e) illustrates the on-slice-time material computation step, whereby user-generated and external data sources, such as scalar and vector fields, from, for example, point-clouds and meshes, are transferred to a volume domain, and can then be used to influence and compute heterogeneous material distributions. A typical example of external data can include a voxel grid containing an n-dimensional property per voxel, describing relative material distributions, where each voxel describes
a probability for a material to be deposited. As such, the provided volume can be coarser then the actual resolution of the printer whereby an actual material droplet description will be computed from the coarser volume during slice-time. We can separate object-representation and material-representation for the purpose of slicing. Figure 12 (f) illustrates an example where several different material computation domains can be combined through common layering operations. Finally, Figure 12 (g) shows the process of material dithering, using a modified version of Floyd-Steinberger [43] error diffusion dithering, where - for each material available to the 3D printer - a set of complementary slices is generated. These slices are directly input to a custom bitmap-printing system which controls the deposition of material droplets by the 3D printer, such that no segmentation of material dithered slices to STL files is needed. This allows the production of objects with large volumes while still enabling continuous material distributions. An example of which is shown in Figure 14.

Figure 14 Object cross section illustrating variations in material composition of an object 3D printed with 3 different materials. (a) Shows the composition of all 3 materials. Sections (b), (c), and (d) contain bitmaps that specify the droplet deposition for every material per object slice. Section (d) shows a close-up of section (c) whereby white pixels indicate material droplets deposited at each location.

To leverage the possibilities enabled by the design of data-driven material property variation during slice-time, we showcase function-driven advection as one example for a hybrid method to generate and influence high-resolution and heterogeneous material distributions. We denote by $m(t_0, x(t_0))$ an initial material distribution and describe the evolution of $m$ through a velocity field $v(x)$, defined at all positions, by the advection equation $\frac{\partial m}{\partial t} + \nabla m \cdot v(x(t)) = 0$. Using the framework shown in Figure 12, we use a coarse volumetric representation of the initial material distribution of the confining object, as well as either a functionally defined or an externally given vector field, as a
secondary volume-data set, in the on-slice-time computation step shown in Figure 12 (f). Lagrangian paths can be generated by integrating the flow. By performing a few steps of semi-Lagrangian advection [44] using a fourth order Runge-Kutta method, on only a few slices at a time, we can defer and distribute complex computations towards individual slice generation. Further modification can be achieved such that a simple diffusion term can be incorporated, or materials can be perturbed along the gradient of a predefined distance field. This, combined with the framework described earlier, enables the evaluation and transfer of data-sets in the material generation steps - as shown in the design case study given next - during slice generation. Further data-driven 3D printed variations using a Stratasys J750 full-color printer and designed implementing our methods are presented in Figure 15.
Figure 15 A collection of three general examples of the DdMM approach, illustrating an array of internal material compositions achieved through the implementation of the described methods to achieve visually complex patterns. Such material compositions are uniquely obtained through our computational framework in combination with on-slice-time advection. The first row shows an example of advection driven by a given velocity field. The second row shows a volumetric data set where advection in the normal direction is used to create a diffusive effect in dense areas. The third row shows a periodic implicit function perturbed by a velocity field. For each set of 3D printed objects, the two photographs depict the object from different viewing angles. Photos: Mediated Matter.
4.3.2 Data Driven Design

To demonstrate the DdMM approach in a design setting, we present Lazarus, a wearable mask designed to contain the wearer’s last breath. The mask was designed as part of a collection whose design is ongoing, speculating upon, and offering a new interpretation of the ancient death mask. Traditionally made of wax or plaster to represent a person’s face following death, Lazarus serves as an ‘air urn’ memento that is 3D printed, carrying a loved one’s final exhale. As such, the mask offers a new form of portraiture combining the wearer’s facial features while performing as a spatial enclosure for their last breath. The mask’s surface area is modeled after the face of the dying, while its material composition is informed by the physical flow of air and its distribution across the surface. Unlike its traditional hand-made analog, the design of Lazarus is entirely data driven, digitally generated and additively manufactured, approaching the resolution of the physical phenomenon it is designed to capture. Data fetched to inform the distribution of air flow can be acquired from the wearer, or, it can be digitally generated by a computational process incorporating the wearer’s data, thereby creating a unique artifact perfectly customized to fit the wearer and her last breath.

For this speculative design, and its related (and specific) application, our design approach is illustrated in Figure 16 and can be implemented as follows. First, the data designated to drive the material distribution is acquired or generated. In this example, only generated data is used, while - as stated above - external data-sources can also be employed and used with the described method. This data is then transferred from the domain of its origin (e.g. a human face), to a target domain (e.g. a mask designed around the human face). As the data from the original domain is insufficient to compute material distributions in a volumetric domain, this step is necessary to render the provided data suitable for further computation and evaluation. The collected data sources are subsequently used to inform the generation of material distribution. The material generation step is performed during slice generation, and as such, allows for the controllable design of material distribution at the resolution of the printer, while optimizing the use of available computational resources.

To simplify, we denote the closed parameterized surface (i.e. the face of the wearer) as \( \partial \Omega \), and the target volume domain (the mask) as \( \Omega \), shown in Figure 16 (d) - left and right - respectively. In this workflow, we implemented three different data-sources to drive material generation. First, as shown in Figure 16 (a), a heat map derived from solving for \( u(\cdot, t) : \partial \Omega \rightarrow \mathbb{R} \) in the adapted heat-
equation[45] \[ \partial_t u(x,t) = k\Delta_{\Omega} u(x,t) + \frac{Q(x,t)}{c_p} \], where \( \Delta_{\Omega} \) is the surface laplacian, and an initial temperature \( u(x, 0) = u_0(x) \), is given. While in this case, the heat map is synthetically generated, it could equally well be acquired from a thermal imaging camera where the acquired data can be mapped to \( \partial\Omega \) and similarly processed at a later time in the workflow, as described below. Secondly a geometrically determined normal-map as shown in Figure 16 (b), from \( \partial\Omega \), determined by \( n(s) = \frac{(\partial s_1 X(s) \times \partial s_2 X(s))}{|\partial s_1 X(s) \times \partial s_2 X(s)|} \) is generated. Lastly, we use a velocity field (Figure 16 (c)) acquired from a computational fluid simulation mimicking simplified human respiration where \( \partial\Omega \) was used as a rigid collision object.

Figure 16 (d) shows the target 3D object, which was designed specifically to fit to our region of interest. On this “template”, we model material distributions such that they are informed by the combined source data-sets. In order to transfer the previously computed data-sources to the volume domain, we use three different methods; Extrapolation, re-representation, and a simple change of domain. First, for \( \Omega \), we generate a signed distance field[46] \( d_{\partial\Omega} (x) = s_{\partial\Omega} (x) \cdot m_{\partial\Omega} (x) \), and \( m_{\partial\Omega} (x) = \inf_{y \in \partial\Omega} d(x,y) \) and \( s_{\partial\Omega} (x) = \{-1 \text{ if } x \text{ is interoir } \partial\Omega, 1 \text{ if } x \text{ is exteroir } \partial\Omega\} \). Similarly we generate \( d_{\Omega} = s_{\Omega} (x) \cdot m_{\Omega} (x) \), and \( m_{\Omega} (x) = \inf_{y \in \Omega} d(x,y) \) and \( s_{\Omega} (x) = \{-1 \text{ if } x \text{ is interoir } \Omega, 1 \text{ if } x \text{ is exteroir } \Omega\} \). For the heat map, we use a one-way extrapolation[47] of \( u \) from the interface along the normal-direction such that \( u + (\nabla u \cdot \nabla d_{\partial\Omega}) = 0 \) as depicted in Figure 16 (e). For the normal-map, we choose to re-represent by \( \nabla d_{\Omega} \) instead of the surface normal, as \( \nabla d_{\Omega} \) is defined over all of \( \Omega \). In a similar fashion, other geometric properties such as curvature can be made useable to the volumetric domain. Finally, for the velocity field in Figure 16 (g), we simply change the region where the field is sampled from \( \partial\Omega \) to \( \Omega \). We note, that the transfer step is not necessary if the provided data is already specified in the target domain. However, this example serves to outline how this transfer can be accomplished if the provided data-sources are not specified as needed.
Figure 16 Visualization of the design approach for Lazarus. In (a), (b) and (c) data-sources are generated. (a) shows the generated heat-map; (b) shows the generated normal-map and (c) shows the velocity-field computed over $\partial\Omega$. In (d), the data-sources are transferred to the object of interest, which is detailed in (e), (f) and (g).

From this transferred data, we compute material distributions implementing a three-step strategy. The contribution of each external data-source is shown in Figure 17, where the first material is depicted as opaque, and the second as transparent. The heat map provides coarse initial guidance for the grading of material distributions, such that areas with high temperature use the first, transparent material while regions with low temperature use the second, opaque material. Afterwards, the velocity field perturbs material voxels according to the above described advection process. The normal field,
in turn, aligns the flow and confines the emerging patterns to the contour of the face as well as its surrounding boundary, by projecting the velocity to the gradient of $d\theta$. As described above, by providing data-sources during the generation of each slice, this processes can be carried out per slice. This allows the material distribution to be computed at the resolution of the printer without requiring significant computational overhead, and, as such, high spatial complexity in the patterns generated can be achieved.

Figure 17 Volumetric visualization of the contribution of each original data-source for the generation of internal material distributions. Grey areas represent VeroWhite (RGD835) material and transparent areas represent VeroClear (RGD810) material. For clarification purposes, only the distribution of the rigid white material in the final 3D printed prototype is emphasized (see also Figure 18). (a) Initial material distribution; (b) Contribution of the heat-map as an indicator for material grading; (c) Contribution of the normal-map to align advection with the geometry of the face, here visually empathized by a displacement; (d) Contribution of the velocity field to perturb material-distribution; (e) Final combined effects in a pre-visualization.

The resulting object was produced on a Stratasys Objet 500 Connex 3 printer [48] with opaque VeroWhite (RGD835) and optically transparent VeroClear (RGD810) materials, and is shown in Figure 18. Throughout the entire design process, the sequential design iterations were all reviewed using standard volumetric visualization methods [49], as shown in Figure 18.
Designed by Neri Oxman and the Mediated Matter Group in collaboration with Stratasys. Using a functional advection workflow, the resulting 3D printed mask - printed from rigid white and transparent materials - is shown alongside its corresponding 3D rendering. Photos: Yoram Reshef, courtesy of Mediated Matter.

While the case study in this example is design driven, the above described methods can be employed for many different applications. For example, this method can be used for direct visualization of data sets, such as z-stacks acquired from biomedical imaging studies, physical visualization of multi-field computational simulations, or visualization of point-clouds acquired from geospatial sources. Furthermore, these external data sets could be functionalized and used for the evaluation of heterogeneous material modelling methods. This could potentially allow for the production of materially optimized prosthetic sockets [32], in finite element analysis for material optimization, or even materially adapted habitats for microbial assemblages.
4.4 Conclusion

The DdMM computational approach and its related case study presented herein, serve to demonstrate a data driven material modeling work-flow, combining slice processing and material distribution generation with high-resolution bitmap-based 3D printing. It provides a powerful tool for the generation of complex 3D objects with volumetric heterogeneous material distributions.

In addition to capturing, processing, generating and digitally fabricating complex volumetric material distributions shown herein, the DdMM computational approach and its related methods can contribute to the enablement of a wide array of applications including the production of high-resolution lens arrays, detailed surface topographies and lattice structures, as well as protocols associated with the retrieval of material properties from geometric representations. Such applications and related protocols could be produced with on slice-time methods at the native resolution of the printer, without the need to design or generate additional geometrical content and as such with minimal memory overhead.

4.5 Acknowledgments

The authors would like to thank Naomi Kaempfer, Director of Art, Fashion and Design at Stratasys, and team members - Gal Begun, Boris Belocon and Yoav Bressler - for their insights and dedication in producing Lazarus. The company’s support has enabled the use of the Stratasys Objet 500 Connex3 color, multi-material 3D printer and Stratasys J750 seven material printer. The authors also wish to acknowledge Yoram Reshef for his photographs.

4.6 Author Disclosure Statement

No competing financial interests exist.
5 VOXEL-PRINTING FOR DATA FABRICATION

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5.1 Abstract

We present a multi-material voxel printing method for the physical visualization of data sets commonly associated with scientific research. Our method enables fabricating discontinuous data types – such as point-cloud data, curve and graph data, image-based data, and volumetric data – by leveraging voxel-based control over multi-material 3D printing. By converting such data sets into dithered material deposition descriptions, we demonstrate – through modifications to known rasterization processes – that data sets frequently visualized through rasterization can be converted into physical, materially heterogeneous objects. This enables to bridge the gap between digital information representation and physical material composition. We evaluate the visual and physical characteristics and features of our method, assess its usability in the production of physical constructs, detail the conversion of data sets for multi-material 3D printing, and show exemplary 3D printed data sets produced by our method hinting at potential applications across scales, disciplines and problem domains.
5.2 Introduction

The physical visualization and representation of data is interwoven across ages with human culture, communication, and education. To date, the representation of data sets is largely achieved through screen-based media visualization. Scientific visualizations – for example – account for a wide range of virtual information displays; be it in form of volumetric rendering of patient data obtained from MRI or point-based rendering of geospatial data obtained from photogrammetry methods. Due to advancements in 3D printing, the accessibility and affordability of digital fabrication workflows and tools – such as additive manufacturing – can be expanded to enable the ‘resurrection’ of such data in its physical manifestation. Consequently, the representation of data sets in physical form through digital fabrication has recently emerged as a research area and practice [1]. More broadly, the manifestation of data in its physical form is often collected under the term data physicalization [2] or physical visualization [3].

Multi-material 3D printers [29] deposit distinct build materials through a layer-by-layer ink-jet like printing process to construct high resolution 3D objects [50]. Such high levels of spatial control in manufacturing is achieved by defining a set of layers in a raster file format – at the native resolution of the printer – defining, in turn, the ‘material identity’ of individually assigned droplets and their placement in three dimensional space. The set of layers can, for example, be processed as binary material assignments within a voxel matrix – a single voxel assigned for each depositable material unit at the resolution of the 3D printer. This process defines where a droplet will, or will not, be placed. A printer can then process these droplet deposition descriptions, to digitally fabricate heterogeneous and continuously varying material composites. This approach is often described as bitmap-based printing [51] or voxel-printing [32].

In this paper, we present an approach to physical data visualization through voxel-printing, and showcase how voxel-printing can be made a vehicle for physical data visualization. Importantly, this approach enables direct digital manufacturing of numerous data sets commonly found in scientific visualizations, without the need to create intermediate representations for 3D printing. We show that – through voxel-printing methods – many of the representations commonly utilized for data visualization can be directly fabricated through rasterization. This effective method points
towards the elimination of the digital/physical divide bridging digital on-screen data and their physical manifestations.

The paper is organized into three sections. First, we review recent developments in the field of physical data visualization – especially as they relate to 3D printing – and describe relevant concepts from the field of multi-material 3D printing. Following, we provide an overview of how to derive 3D printable descriptions utilizing voxel-printing, investigating the visual characteristics of producible artefacts. Next we present how such methods can be adapted to a range of distinctive data sets showcasing an array of exemplary 3D printed objects representing different research disciplines. Lastly, we discuss future potential applications that become enabled through the implementation of our voxel-printing method for physical visualization.

5.3 Related Work

Information visualization aims to map, process and represent data in visual formats [52] from which – through perception, vision and computer-aided interaction – insights can be gathered by a user. While conventional screen-based media visualizations are known to be largely successful, it has been argued that physical manifestations of data sets can leverage active as well as spatial perception skills, enabling a more comprehensive understanding of presented information [53]. Furthermore, considering increasing availability of digital fabrication facilities, and given the accessibility of CAD tools, physical visualizations are becoming more widespread. Consequently, additive manufacturing tools and technologies are playing an increasingly important role in the creation of passive and active data sculptures, as well as in the manifestation of typically screen-space constrained visualizations in the physical realm.

One of the earliest and still popular additive manufacturing methods for the fabrication of scientific visualizations in physical form is the use of powder based binder jetting [54]. This method has become particularly popular as it enables the digital fabrication of boundary representations with associated colored-textures, which – aside of shape-based control – enables the use of color as a discrete parameter for the encoding of color-based information on the object’s surface. While this
enables the production of 3D colored models, the supplied data format must be given as a closed 2-
manifold triangle mesh with associated texture or vertex attributes. As such, common representations
used in scientific visualization must be converted to such boundary representations through geometry
processing tasks, which may in turn result in partial loss or alternation of the data set at hand.
Alternatively, crystal laser engraving provides a mean to directly fabricate discontinuous data sets [18].
Here, a pulsed laser beam creates a large number of etched points captured within an optically
transparent material. However; as this method works by introducing damage into a material, it is
restricted to monochromatic visualizations, and is limited by the spatial density of dots and the lack
of color. Furthermore, the enclosing geometries are mostly constrained to simple forms such as
rectangular blocks. Complex data-sculptures — such as objects visualizing sound, landscapes or graph-
like structures — are often fabricated using Selective Laser Sintering (SLS), where a laser fuses
deposited powder in a layer-by-layer fashion to form a solid object. Due to its ability to fabricate
complex geometries without support scaffolds, it is suitable in cases where intricate objects are
required. However, given the very nature of the fabrication process, it does not enable the fabrication
of parts with varying translucency or color.

In comparison, multi-material 3D printing with photopolymeric materials enables the use
of several different materials at once. This allows the use of dedicated cyan, magenta, yellow, black,
white, and transparent resins to create full color models. The ability to create objects inside
transparent enclosures enables the physical visualization of compact n-manifolds ($n \leq 3$) such as
unconnected point cloud data, lines and curves, open surfaces, and volumetric data. While the 3D
printer can deposit multiple materials; each and every location within the build platform can only be
inhabited by a single material droplet. However, commercially available multi-material 3D printers
commonly have a build envelope of 500mm by 400mm by 200mm with a droplet deposition
resolution of 600dpi and 300dpi respectively and a layer separation of down to 12μm, which results
in 929 billion individually addressable voxels. This high-resolution build space enables two key
characteristics relevant for physical visualization:
Visual gradients: by varying the spatial and local density of droplets belonging to different materials, visual gradients in color and opacity can be achieved.

Preservation of detail: a clear enclosure volume can be deployed, which enables the digital fabrication of highly detailed structures with fine features-sizes that can be perceived reliably.

While multi-material 3D printing is used in sophisticated design processes of advanced products [55] with complex geometries [56], only recently has this approach been used for the generation of data-sculptures, with data informed patterns [50].

5.4 Physical Visualization through Voxel-Printing

5.4.1 Method

Similar to [50] and [51], we use high-resolution material dithering to achieve optical transparency and color gradients in the produced artifacts. As a general rule – and for a given data set – an approximating hull must first be generated; as either an accurate boundary representation, a convex hull or a simple bounding box. Any volume inside the approximated hull that is not occupied by materials corresponding to the data sets, is specified to be occupied by transparent material. The dimension of the hull – combined with the resolution of the 3D printer – determines the number of layers the printer will fabricate for a given representation. Then, for each layer, internal material information is computed, which is sourced from the given data set. Such ‘per layer’ material information is then materially dithered into material droplet deposition descriptions, from which it is determined where to deposit which material. The dithering process [35] converts material mixing ratios to spatial droplet deposition instructions. Through the high-resolution deposition of different materials during print time, visual gradients can be achieved. An example of this process is shown in Figure 19, where opaque and transparent materials are mixed at different ratios resulting in a gradient from opaque to transparent.

However, material mixing ratios do not directly translate to perceivable, optical properties. Only objects with high clear material content show differences in transparency, while objects in the
range of 0-70% transparent material content barely exhibit any variation in transparency, especially in the thick regions of a given sample (Figure 19). This information is important for the visualization of volumetric data, as a linear mapping from information to material mixing will not yield linear changes in perceivable transparency.

Figure 19: Variability in optical transparency as a function of transparent : opaque resin mixing ratios. (a) A typical single layer acquired through material dithering. The layer shows distinct transparent and opaque material voxels along with their associated material droplet mixing ratios. This raster-description instructs the printer to deposit transparent and opaque material droplets, whereby white pixels in the bitmap result in physical material droplets. White pixels in the upper row describe the opaque material distribution, while the white pixels in the lower row describe the transparent material distribution. Here, numbers relate to transparent material ratios, and in combination, the two material descriptions result in an opacity gradient. The corresponding 3D-printed objects are shown in (b). Here, it is apparent that visual characteristics are not linearly related to material mixing ratios. In (c) we show that perceivably separable differences accumulate at mixing ratios of high clear material content. Small changes in additionally deposited opaque material droplets can have a dramatic change in perceived opacity.
Modern multi-material 3D printers can offer a resolution up to 600 dpi in the horizontal build space axis and layer separations as small as 12 microns in the vertical axis. This allows for the physical visualization of finely detailed information. The resulting 3D printed objects would be too fragile or otherwise – in the case of an unconnected point cloud – impossible to 3D print as self-supporting structures, but they can easily be produced within a transparent enclosure. In this way, it is possible to additively manufacture feature sizes below 1 mm that closely resemble what is possible to visualize on screen.

Given the nature of the dithering process, highly transparent features will begin to blur and may appear fuzzy, as mixing ratios with high clear content will result in overly dispersed droplets of opaque material as is shown in Figure 20. Here, simple geometric features of different sizes – such as lines and dots – enclosed within transparent shells, were 3D printed to evaluate the feature-sizes range of producible objects. The geometric elements are made of resin mixtures with different ratios of transparent-to-opaque materials. These models demonstrate that elements made out of pure opaque material are perceivable even at smalls scales – specifically even at a diameter of 0.01 mm in case of a line or a diameter of 0.1 mm in the case of a sphere – while elements with higher clear content are barely visible at that scale. For visualizations, such feature-sizes must be considered; and thinner elements have to be mapped to material mixing ratios of higher opaque content if they are to be retained.

Models shown herein where printed on Stratasys Objet500 Connex (two material), Stratasys Objet500 Connex3 (three material) and Stratasys J750 (six material) 3D printers. VeroClear (RGD810) was used as transparent media, while for colors, VeroWhitePlus (RGD835), VeroBlackPlus (RGD875), VeroYellow (RGD836), VeroCyan (RGD841) and VeroMagenta (RGD851) were used. The 3D printing systems stated above make use of a support material to stabilize objects while they are being printed. The support material is removed after the print has been completed, resulting in surface roughness at the interface, where the support material connects with the actual model material. For transparent materials, this may result in partially diminished optical clarity. However – since this is merely a surface effect – optical transparency can be fully restored by polishing and lacquering the 3D printed part with a clear-coat.
Figure 20: Variability in optical transparency as a function of transparent : opaque resin mixing ratios and feature size. (a) Line elements with a diameter range of 1.0mm - 0.01mm were 3D printed within transparent enclosures with mixing ratios of (LS) 0% transparent (fully opaque) and 90% transparent material (RS). All fully opaque lines are visible, while the lines with 90% transparent material content are visible only when the diameter is equal or bigger than 0.3mm. Similarly, the dots shown in (b) exhibit similar behavior, where opaque dots with a diameter of 0.5mm are clearly visible, while more transparent dots are only clearly perceivable at larger sizes. (c) Shows a close-up of the printed objects with geometric elements printed with pure opaque material content. While the features are very small and individual elements start to vanish, a 0.1mm dot on the left and 0.01mm line on the right are still noticeable, which highlights the ability of our method to fabricate very fine features.

5.4.2 Point Clouds

Point clouds are often encountered in scientific visualizations, frequently used for geospatial imaging. They are particularly prominent in geographic information systems – commonly obtained by LiDAR – where they are used to capture digital elevation maps [57] or to observe the development of
agricultural [58] or urban environments [59]. Further areas of application include archeology — where point clouds are used to capture and preserve artifacts and sites [60]. A point cloud is usually defined as a set of points represented by its coordinates, where each point may contain additional properties such as color, normal direction, luminance etc. Additive manufacturing typically requires boundary representations; thus a given point-cloud must first be converted through processes such as poison surface reconstruction [61], resulting in a triangulated mesh that is usable for common 3D printing workflows. However, if a closed surface is not a necessity by design, and the given point data set is particularly disconnected or fragmented, volumetric voxel-printing presents a valuable alternative. Rather than reconstructing a surface, we can directly rasterize each point to a layer used in the multi material 3D printing process. This way, we can directly use the point cloud as input, without applying further conversion steps, which otherwise may alter or distort the original data.

![Diagram](image)

**Figure 21:** Point cloud data processing workflow. (a) Initial point cloud data containing point-specific attributes. (b) Determination of containment for the point-cloud in the form of an axis-aligned bounding box. (c) The containment, combined with the available printer resolution determines the dimension and number of the generated layers. (d) The point cloud is processed for each layer. (e) For each pixel within a single layer, the point cloud is queried for nearby points, which are interpolated and rasterized to generate the final material data. (f) Material information is dithered into binary material deposition descriptions. Here, white color denotes deposition of material at the pixels' location in the build space, while black denotes the absence.
The conversion of point cloud data to 3D material deposition description is shown in Figure 21. First, the dimensions of an enclosure are determined, which acts as a transparent vessel inside which the point cloud is contained. From this enclosure, the dimensions and number of layers required to build up the volume of the 3D print are calculated. We traverse the point cloud in a layer-by-layer fashion in a direction perpendicular to the print bed, generating a raster-image for each layer (Figure 21 (d)). Each layer’s pixels carry information referencing their position in space (Figure 21 (d) right). We then use this information in combination with layer height to spatially query — for each pixel within each layer — the point-cloud for subsequent 1 to n nearby points within a specified distance threshold (Figure 21 (e)). This spatial query can be efficiently implemented using common spatial data-structures. Utilizing n queried points; material selections per voxel are implemented. If the distance from one or more of the queried points is smaller than a given threshold, the queried point information is used to determine material-information. Depending on the information available from the points, this can be done in several ways. One way is to filter — for example — the queried n closest points by distance weighted averaging and assign this value to the querying pixel. If a radius property is associated with the points — and if the distance from pixel to point is below this radius — we can discard the point and skip further evaluations. Pixels that are part of the enclosing surface but are not part of the point-cloud are designated to be printed with an optically transparent material. Finally, the layer containing material information is dithered into the material droplet deposition descriptions in the form of the binary raster file described above (Figure 21 (e)). This process is executed for each generated layer, where a layer is generated at 3D printer-specific vertical layer deposition heights (for example, every 12 μm) from the enclosing object’s lowest to highest positions. Two examples using this method are shown in Figure 22.
Figure 22: Representative 3D printed models from point cloud data sets. The statue shown in (a) is based on photos acquired in Bali, Indonesia from Tampak Siring Temple. The point cloud consisting of 3.6 million points was generated through automated cloud-based, photogrammetric processing service Culture 3D Cloud, provided by the CNRS in France[62]. The digital elevation model of the moon shown in (b) is represented through a point-cloud of 21 million points. The data was captured by the NASA Lunar Reconnaissance Orbiter, which was launched in 2009 and has since orbited the moon “creating a comprehensive atlas of the moon’s features and identifying available resources.”[63] The data, available online[64], was acquired by the Lunar Orbiter Laser Altimeter, one of the instruments on the orbiter[65].

Figure 22 (a) shows an archeological point cloud consisting of 3.6 million points, generated through photogrammetry methods [60] provided through a cloud-based photogrammetric processing service [62]. The point cloud was implemented in its original obtained form with minor post processing operations. In addition to 3D coordinates, a RGB color attribute was associated with each point which was extracted from the accompanying image data. The point radius in Figure 22 (a) was given as 0.5mm, resulting in a surface thickness of about 1mm and an overall opaque, solid appearance of the printed object. Figure 22 (b) shows a digital elevation model of the moon, provided by NASA and captured by the Lunar Reconnaissance Orbiter [63]. The data consists of 21.2 million points with
color information which was generated as a function of surface elevation. For this example, a point radius of 0.125mm was used, resulting in an approximately 0.25mm thick, semi-translucent surface.

5.4.3 Volumes

Volumetric data can be obtained from numerous fields of science. In the medical sciences, for example, volume-based data are generated via imaging sources such as magnetic resonance imaging and computed tomography. In simulations, volumetric representations are used for spatial domain discretization in finite-difference and finite-element approximations of partial differential equations for modeling the behavior of fluids and solids. A volume is a representation of a discretized scalar or multi-dimensional field. To represent volumetric data, the use of regular or adaptive grids – where each grid node stores one- or multi-dimensional information – is common. Another representational strategy, more commonly found in simulation of deformable objects, is the tessellation of the interior of a domain using Delaunay tetrahedralization, assigning properties to vertices, edges and faces of the tetrahedral mesh. Again, common additive manufacturing processes use surface representations that – for a given volume – can be achieved by employing ISO-surface extraction methods such as marching cubes [66] or dual contouring [67]. However, these methods produce visible loss in detail when compared to the original data set, since volumetric gradients of the original data cannot be reproduced with these methods. Moreover, in order to assign uniquely different materials to distinct regions, distinctive domains must be isolated through segmentation methods [68], which can further complicate data preprocessing for 3D printing. By employing voxel-printing methods, superfluous preparation overhead and loss in detail can be prevented. Since control over every individual material voxel in the 3D printer’s build envelope at a resolution as high as 600dpi can be achieved, the addressable material voxel matrix has a resolution which approaches and at times exceeds the volumes commonly used for imaging or simulation. This approach enables us to directly translate volumetric property gradients to 3D printable material gradients. As such, if preservation of the given data is of importance, including volumetric color, transparency, or general material property gradients, voxel-printing presents a valuable alternative to current practices. As a proof of concept, we describe a
workflow for translating volume property gradients to transparency gradients using transparent and opaque materials.

Figure 23: Volumetric data processing workflow. (a) illustrates initial volumetric data of a 3D object; (b) illustrates the generation of an external enclosure for the volumetric data set. (c) Layer dimensions are obtained; (d) Layers are processed in parallel. Here, a voxel intersecting a layer is shown; (e) For each pixel within a given layer, its position information is used to sample the volume assigning per-pixel material data; (f) Material information is dithered into binary material deposition descriptions. Here white denotes deposition of material at the pixels' location in the build space, while black denotes no deposition.

Our method to additively manufacture objects that are represented as volumes is given in Figure 23. First, an outer enclosure containing the volumetric data is specified, from which the dimensions and number of layers containing material information, are calculated. This phase can be as straightforward as assigning a bounding-box or an extracted ISO-surface as shown in Figure 23 (b). However, if the source volume has a clear distinction between voxels not representing internal information and those that do, this boundary description is redundant and a 3D printable surface can still be reconstructed from the volume alone. Yet, if the data set is highly volumetric and discontinuous – as can be seen in computational fluid dynamics – such an enclosing shape is important. Similar to our process of printing point clouds, the volume data is processed layer-by-layer (Figure 23 (d)) and for every layer, a material description in form of a raster-file format is generated. As previously described, the spatial information of the pixel is used to sample the volume and interpolation methods such as tri-linear
interpolation can be used to determine the pixels' material information (Figure 23 (c)). Pixels placed within the outer shell, but that are not occupied by the volumetric data itself, will result in transparent resin droplet information. Voxel data can be directly converted to a rasterized description by matching the source volume's voxel resolution to the printer's droplet-voxel resolution. Using this approach, however, does not permit the visualization of intermediated transparencies potentially encoded in this voxel. Hence, interpolation of the voxel data for each pixel in a printing layer might be necessary for best results (Figure 23 (c)). As before, each layer is dithered to raster files, containing the material droplet deposition descriptions (Figure 23 (f)).

Figure 24: Representative 3D printed models from volumetric data sets (a) A computational fluid dynamics simulation of the chaotic mixing of white, green and transparent fluids; (b) A CT scan of the left hand of a patient with arthritis. The radio density information stored in the CT volume is mapped to a material gradient of opaque white and transparent material. White areas represent bone with the highest density and transparent regions represent skin and soft tissue, while semitransparent gradients in between represent lower density bone, muscles and tendons.
Figure 24 shows two examples of volumes, additively manufactured through our method, where properties from the source volumes are converted to transparent material gradients. Figure 24 (a) represents an example, where the flow of two fluids is simulated inside a volume, resulting in chaotic mixing and the formation of realistic patterns. This example closely resembles the visual quality of natural phenomena, like— for example— ink drops mixing in water, with the difference that the computational simulation in combination with the additive manufacturing is completely reproducible, unlike a physical experiment. Figure 24 (b) shows a cross section of the volume of a patient’s hand with arthritis that was captured through CT scanning. The data stored in the captured volume represents radio density in the Hounsfield scale, which represents the relative inability of electromagnetic radiation to pass through different tissues and bone in the human body. On screen, these data sets are usually visualized as grey scale gradients, where white represents the densest bone areas and black represents air, with the intermediate gray-scale values corresponding to other tissue types in the patient. In Figure 24 (b), the radio density gradient in the captured CT volume is converted to a material gradient of opaque white material (bone), and completely transparent material (skin/soft tissue). An ISO-surface generated from the CT-scan was used as the outer, volume containment. The amount of detail and high fidelity of the seamlessly varying transparency gradient in the above examples shows the strength of our approach, especially for the additive fabrication of volumetric data. In contrast, common printing workflows, employing segmentation strategies, are not capable of producing this level of visual quality.
Figure 25: Brief description of the conversion of tetrahedral meshes; (a) to 3D printable droplet depositing descriptions. Here – for each layer – nodal-data from tetrahedral-mesh intersecting with the material description layer is interpolated for each pixel occupied by a tetrahedron, through barycentric interpolation; (b). An example of this approach is shown on the right (c). Here a tetrahedral mesh is used to simulate the deformation of a compressed cube, through finite element methods. High deformation is encoded as red opaque material and low deformation is encoded as partially transparent white material.

Similarly to the process illustrated in Figure 23, Figure 25 shows the conversion of a volume represented as a tetrahedral mesh. In this example, the tetrahedral volume is used to describe the deformation of a body. For every tetrahedral-element in the volume, material information can be calculated by barycentric interpolation of every tetraeder’s vertex. Figure 25 (c) shows an example of this approach. Here, finite element simulations were used to investigate the buckling of a hollow tube under compression. The deformation is encoded in gradients of color and transparency. White/transparent areas indicate no deformation, whereas red/opaque areas indicate regions of high deformation.

5.4.4 Curves and Graphs

Visualizations using curves and graphs are one of the simplest techniques to present complex information in a reduced and understandable fashion. While graphs and networks usually represent relationships, curves and line-based visualization are often constructed to convey a sense of motion where it is not perceivable. For example, superposition of Nuclear Magnetic Resonance Spectroscopy
structures of macromolecules complexes are often visualized graphically [69], while velocity and magnetic fields are often showcased by flow lines, generated by tracing particles in the given fields. For common printing workflows, such one-dimensional curve and graph data has to be converted to closed 2-manifold meshes. For curves, this can be easily achieved by sweeping operations, while for graphs and networks, algorithms generating polygonal struts are common [70]. The generation of surface geometries causes significant computational overhead, especially for data sets with many lines, curves and intersections. Therefore, we propose a method that integrates curve and graph data directly in the voxel-printing process, without the need to generate a mesh structure. As with point and volume data, this process can be highly parallelized, enabling the rapid processing of large data sets.

Figure 26: Curve and graph data processing workflow (a) and (b) For the input curve or graph data, an enclosure is specified, which can be a convex hull, bounding box or any other shape. (c) The enclosure specifies the dimensions and number of printing layers, which are required to contain the material description of the data set. (d) The data set is traversed layer by layer. (e) For each pixel in each layer, the closest curve or line segment is queried and properties associated with the curve or line segments are interpolated. (f) The interpolated data is then used to generate material information that is dithered into binary material composition layers.

Figure 26 illustrates our voxel-printing method for processing curve or graph data. The input data is stored in a hierarchical, spatial data structure to be efficiently queried in the following steps. Properties like color, transparency, etc. can be stored in the vertices of line segments or for example in the case of Bezier curves, in its control points. First, an outer shell is specified (Figure 26 (b)), because, as with
point clouds or volumes, a clear enclosure is required when printing thin lines, fine details, or discontinuous curve and line elements. The shell can be in the form of a convex hull, a bounding box or any other shape. The enclosure specifies the dimensions and numbers of printing layers, which are required to confine the material description of the data set (Figure 26 (c)). The input data is traversed layer by layer and for each pixel in each layer, the spatially closest line segment or curve in a given distance is queried (Figure 26 (e)). With this method, it is possible to render graphs and curves with constant (and potentially very thin) line widths. Properties that are associated with the input data set are interpolated at the point on the curve or line segment, which is closest to the current pixel. This can be done by linear interpolation between line vertices or curve control points. The interpolated values are used to specify material information that is stored in a raster file format for every layer. Lastly, every material information layer is dithered into binary material composition layers, one for each material that is needed to fabricate the input data set (Figure 26 (f)). With this method, we are able to efficiently render fine line structures as a tangible object, which resemble the resolution of line and curve visualization on-screen. Especially very detailed visualizations with many discontinuous elements, as they arise, for example from flow line visualizations of velocity fields or other force fields, become producible through our approach.
Figure 27: Representative 3D printed models from curve and graph data sets (a) Crystallographic protein structure of the Apolipoprotein A-I, taken from the Protein-Data Bank (pdb-code: 1AV1) [71]. The individual atoms of the protein are encoded according to the following color scheme: orange: N, cyan: C, green: O, yellow: S. The data set consists of 6588 points (representing each atom) and 13392 line segments, representing the interatomic bonds. (b) White matter tractography data of the human brain [26], created with the 3D Slicer medical image processing platform[27], visualizing bundles of axons, which connect different regions of the brain. The original data was acquired through Diffusion MRI, where 48 scans are taken for each MRI slice, to capture the diffusion of water molecules in white matter brain tissue, which is visualized as 3595 individual fibers. The fiber data set consists of a total of 291,362 line segments that are colored according to their orientation in 3D space.

Figure 27 shows 2 different examples of line data sets. Figure 27 (a) shows a reconstruction of the 3D structure of Apolipoprotein A-I, which is a protein necessary for lipid metabolism in the human body. The data was taken from the Protein Data Bank [72], an internet database, which archives the three-dimensional structure of large biological molecules. Proteins from the database can be obtained in the form of pdb-files, that encode all atomic elements and the molecular structure in which they are assembled. Such data is commonly visualized on screen in the form of a ball and stick model, where atoms are visualized as points (with a user defined radius) and their bonds to neighboring atoms are
visualized as line segments. The protein in this example is described through 6588 points and 13392 line segments that are arranged in a torus-like structure. The lines are voxel-printed according to the method described above, whereas the points are processed according the method described in the point cloud section. A tube, that is swept along the middle axis of the protein’s torus structure, is used as a clear enclosure, which was, in this case, more appropriate than a bounding box or convex hull. The individual atoms that make up the protein are encoded according to the following colors: orange: N, cyan: C, green: O, yellow: S.

Figure 27 (b) shows white matter tractography data of a human brain. The fibers in this visualization represent bundles of axons in high resolution, which connect different regions of the brain. This fiber data is created using Diffusion Tensor Imaging, a process that captures the diffusion of water molecules in white matter brain tissue through MRI. The whole visualization consists of 3595 individual, disconnected fibers, where each fiber is represented as a polygonal chain with a total count of 291362 line elements. The line segments are color coded according to their three-dimensional orientation. In this example, an ISO-surface was extracted from the MRI data to act as an easily interpretable transparent enclosure.

5.4.5 Image-Based

Image-based data sets are frequently used to record three-dimensional scientific data, as this format allows for convenient previewing, editing and file handling. There are several approaches to describe three-dimensional spatial situations through two-dimensional images. One approach is to use stacks of images to represent physical volumes. This format of data representation is most prevalent in biomedical imaging disciplines, like radiology (X-Ray CT, MRI, Ultrasound) or confocal microscopy, where physical volumes are observed layer by layer and captured as image stacks. A different approach uses a single image to store spatial information, mostly elevation or displacement, in form of a scalar or multi-dimensional raster format. One such example are digital elevation models in geographic information systems, where height-maps are used to represent topographic surface elevation. Similarly, bump-, normal- and vector-displacement-maps are frequently used in computer graphics.
and visualization, for example to represent depth and surface features in the context of the reproduction of archeological or cultural heritage artefacts [73].

As image-based data sets are already in a raster file format, they are easily integratable into our voxel-printing workflow. An image stack can be converted to a volume data structure, but in the case that there are no operations applied before the printing process that would require a volume representation, it is more efficient to directly work with raster-files as input data. In most cases, an image stack must be pre-processed before the voxel-printing process, to achieve the best, visual results. One important processing step can be noise filtering. Similar to our volume printing approach, transparent resin will be used to produce transparency gradients and convey optical depth in the image-based 3D printed piece. Too much noise in individual images of an image stack will lead to optical turbidity in the final 3D print and as such needs to be reduced. While noise may be low in a single image, it can still accumulate when the image stack is viewed as a whole, therefore in our examples noise reduction was an essential pre-processing step.

After preparation, image stacks can be processed similarly to the approach described in the volume section above. First, an outer enclosure is defined, and from that, the required number and dimensions of the material information layers are calculated. As the input image stack and the material information layers are both in a raster file format, one pixel from the image stack could be mapped to one pixel in the material description. But since several material droplets are needed in order to generate intermediate material compositions, for best results, one pixel from the image stack should be interpolated to several pixels in the material description. Furthermore, multi-material printers operate with a vertical layer height as low as 12 microns and since image stacks are commonly captured with a higher layer separation, the input data also needs to be interpolated in the vertical axis. For the final step, the material description is dithered into binary material droplet deposition descriptions, which instruct the 3D printer to fabricate the data object.
Figure 28: (a) *In vitro* reconstructed living human lung tissue on a microfluidic device, observed through confocal microscopy [74]. Cells responsible for mucous secretion are colored in orange, whereas cells responsible for mucous transport are colored in cyan. (b) Biopsy from a mouse hippocampus, observed via expansion microscopy (proExM) [28] on a confocal microscope. The 3D print visualizes neuronal cell bodies, axons, and dendrites.

Figure 28 shows two examples of voxel-printed image data, which is captured through optical microscopy methods. Figure 28 (a) shows a confocal microscopy dataset that shows *in vitro* reconstructed living human lung tissue grown in a microfluidic device [74]. Cilia, responsible for transporting airway secretions and mucous-trapped particles and pathogens, are colored in cyan, and Goblet cells, responsible for mucous production, are colored in orange. The data set shows physiological pseudostratified airway epithelium exactly as is found in human lungs. The confocal microscopy image stack in Figure 28 (b) shows a magnified tissue sample of a 'brainbow' labeled mouse hippocampus, that was imaged through expansion microscopy (proExM) [28]. With this microscopy method, a specimen is anchored into a swellable gel that physically expands the sample before it is observed under a conventional microscope, which offers results comparable to the use of
specialized super-resolution microscopes. The 3D printed brain specimen resulting from the image stack visualizes neuronal cell bodies, axons, and dendrites.

Figure 29: Elevation map of a portion of the Brooks Range from Northern Alaska obtained from the Elevation Derivatives for National Application (EDNA) [75] database. Material voxels are vertically distributed as informed by the elevation map of the database. Each voxel is color-coded to reflect the degree of slope. Beige color indicates flat areas with low slope, whereas dark brown color indicates areas with high slope.

Figure 29 shows a digital elevation model of a 270 km long portion of the Brooks Range from Northern Alaska. The data was obtained from the Elevation Derivatives for National Application (EDNA) [75] database, which provides elevation data and hydrologically conditioned maps of the USA at 30 m resolution. The provided maps predict information such as slope, water flow accumulation or flow direction, within the elevation. The elevation information – in the form of a grey-scale image – was used to vertically distribute material voxels to create a three-dimensional height map. The individual voxels were colored according to the associated slope map, where beige color highlights regions with low slope, and dark brown indicates mountainous areas with high slope.
5.5 Applications

5.5.1 Conservation and Preservation of Cultural Artifacts

Advancements in workflows and production quality of additive manufacturing tools make 3D printing a valuable tool for preservation and reconstruction of cultural heritage artifacts. Such efforts, for example, can be observed in the recreation of the Temple Lion of Harvard’s Semitic Museum through 3D printing; or the initiative led by Natasha Gangjee, Hod Lipson, and David l. Owen to 3D print Cornell universities’ collection of around 10,000 cuneiform tables from ancient Mesopotamia [76].

The Venice Charter [77] states that the aim of restoration “...is to preserve and reveal the aesthetic and historic value of the monument and is based on respect for original material and authentic documents. It must stop at the point where conjecture begins, and in this case moreover any extra work which is indispensable must be distinct from the architectural composition...”. This implies that common geometry processing tasks utilized in the visualization and reconstruction of cultural heritage – such as laplacian smoothing or volumetric diffusion for hole filling [78] – should be minimized or avoided entirely. However, to achieve watertight representations required to produce 3D printable replicas, such methods are unavoidable. Voxel-printing methods as showcased above can partially eliminate the need for surface reconstruction by printing point-cloud data directly inside transparent shells. Furthermore, the use of multiple color material resins in combination with continuous material gradients between colors achieved by high-resolution dithering allows a high range of color fidelity in the potential replica.

The incorporation of several materials for controlled translucency enables the creation of realistic object replicas with potentially subsurface light transport while flexible material allows to mimic stiffness in the recreated artefact. While solid standards for representation and reliable color-conversion methods have yet to be developed to make voxel-printing valuable for applications in the representation and conversation of cultural heritage, the workflows presented here could help lay the groundwork for the large-scale adoption and utilization of this technology.
5.5.2 Models for Pre-surgical Planning

3D printing as a visualization method is already being used to create models for pre-surgical planning and intraoperative orientation, reducing risks for the patient and shortening the time of surgical procedures [79]. Examples of tangible, medical visualizations include kidney transplants, liver and heart surgeries. The typical process for creating additively manufactured medical visualizations involves a CT or MRI scan, where the scanned image data gets segmented and converted into a set of distinct model parts with homogeneous material compositions per part [68].

This process poses the problem of compromising visual information as -- given a certain threshold -- the initial volumetric data gets converted into discrete parts and volumetric information is lost. A useful strategy to account for such data loss is to segment the scan into several model parts that are printed as an assembly, where every part is assigned a different material. This, for example, was done for the surgical planning of a liver transplant, where the MRI scan was segmented such that the vascular systems could be printed and visualized in different colors [80]. However, such segmentation workflows are time consuming, and the resulting model only coarsely approximates the original scanned data and the high visual fidelity is ultimately lost. In contrast to that, our approach of deriving the material composition of the 3D printed model directly from the scanned data, does not pose a struggle with such problems. We argue that our approach is capable of reproducing the original data faster and with higher visual fidelity, proving to be especially beneficial in surgical scenarios where the additional visual accuracy is needed.

While the examples shown above focus on high-resolution visualization of data through 3D printing of optically transparent but rigid materials, the incorporation of flexible materials in the printing process could potentially allow the reproduction of scanned body parts, like organs, bones and tissue that can be physically dissected as part of the pre-surgical planning process.
5.5.3 Education

There have been attempts to make 3D printable educational models more accessible [81] as well as attempts to integrate additive manufacturing as an active teaching aid within the classroom, used by teachers and students alike. 3D printing is already being used as a tool for the preparation of educational content in fields ranging from anatomy [82] to chemistry [83] and mathematics. This may be attributed to its increasing availability and its ability to fabricate complex yet customized entities at a low cost. Additive manufacturing – specifically when combined with our described methods – could be used to fabricate customized teaching material, which could be used as an alternative for ready-made hands-on educational materials and model kits.

We believe that through the high resolution voxel-printing methods described here, more engaging artefacts can be produced, that reduce the hurdle of information transportation – as well as, consequently – science communication, for specific use cases. The 3D printed display technologies presented herein do not require particular hardware or electricity to function (compared to other data display methods), making them easy to use and accessible. Moreover, they are produced as a single homogeneous solid object, making them robust and durable. We consider the models produced through our methods as valuable additions in classrooms, science centers, museums, etc., where they can either be used as stand-alone visualizations or as tangible accompaniment for existing screen-based visualizations.
5.6 Conclusion

We have shown that a variety of data sets commonly found in scientific visualizations, can be directly fabricated into physical entities by employing voxel-printing. By implementing the methods described herein, we show that the barrier between the digital and the physical can be obviated with ease, enabling a new unified path for the physical visualization of data sets. The resulting physical visualizations closely resemble their screen-based analogues, making this process a valuable addition to common data analysis and visualization workflows. We believe that scientific visualization tools in the future will incorporate methods similar to these described here and allow users to directly – in a click of a button, so to speak, print their visualizations. While digital heritage certainly informs the appearance of physical visualizations at this point, future consideration may be given to material behavior informing materially enhanced experiences of information, including haptic engagement.

5.7 Acknowledgments

The authors would like to thank Boris Belocon and Gal Begun of Stratasys Ltd. for their insights and dedication in producing some of the models shown in this paper. The company’s support has enabled the use of the Stratasys Objet500 Connex two material, Stratasys Objet500 Connex3 three material, and Stratasys J750 six material 3D printer.

5.8 Author Disclosure Statement

No competing financial interests exist.
6 CONCLUSIONS

Figure 30: The depicted data sets are simultaneously processed and 3D printed through the introduced data fabrication framework, which highlights the versatility of the approach and the ability to fabricate high-resolution data without compromising visual fidelity.

The proposed data fabrication framework proposed herein offers a unified approach enabling the production of physical visualizations based on a wide variety of data sets, thus exceeding the visual quality of common workflows and methods as described in section 2.3.
Figure 31: Two observed visual characteristics that arise from the use of the transparent build material; (a) 3D printed areas that were in contact with support material result in a matt finish; (b) Transparency can be easily restored through polishing and clear coat lacquering; (c) Curved surfaces like the brain folds refract light and hamper the view into the inside of the object; (d) However, flat surfaces like the cross section of the brain look highly transparent and do not interfere the view of the data set.

By utilizing the PolyJet printing technology, the fabrication process is autonomous and almost as convenient as printing a document on a piece of paper. However, it comes with two minor drawbacks; both of which are associated with the clear build material. It is impossible to print without support material, which either supports overhanging geometries or acts as a glue layer that stabilizes the data objects during the printing process. Therefore – for example – in the case of data visualization within a clear bounding box, at least one cuboid side facing the printer bed will be contaminated with support material. While support removal is quick and straightforward, it leaves areas that were exposed to the support material with a matte finish. In case of the clear material, the matt finish affects optical clarity as seen in Figure 31 (a). However, as this is just a surface effect, optical clarity can be restored by polishing and clear-coat lacquering the 3D printed artifact, which in the case of a basic geometric shape can be achieved within 15-30 minutes. A further effect observed when working with the clear material is light refraction of curved shapes. As seen in Figure 31 (c), due to the high
surface curvature of the brain folds, the fiber tractography data inside the 3D print is radically
distorted. But when viewed from the opposite flat polished cross section, the brain has a glass-like,
transparent finish, which allows an undisturbed view of the fiber data. This visual characteristic must
be considered when creating curved surfaces for the data object. Considering the advantages that the
clear build material brings to the fabrication process and the fact that the actual data fabrication
process can be completely autonomous, minor design constraints and post processing steps are
acceptable.

Figure 32: Digital volumetric visualization (a) compared to 3D printed, physical visualization (b) of the image stack from
section 5.4.5. For the visualization in (a), the image stack was converted to a volume of 54 million digital voxels. Through
implementation of the introduced image-based voxel-printing process, the image stack was directly translated into a material
volume of 1.1 billion individually addressable material voxels and the 3D printed result faithfully replicates the detail of the
original digital rendering.

Figure 32 shows an image stack visualized through a digital, volumetric rendering (Figure 32 (a)) and
a physical visualization (Figure 32 (b)). The virtual visualization is represented through 54 million
digital voxels, whereas the physical visualization is created from 1.1 billion individual material voxels.
The data object achieves a similar visual resolution and high fidelity as the digital visualization, which
is currently not possible through any other method in the context of data physicalization.
Initial small test prints, done to verify the implementation of the data fabrication methods, were executed on a Stratasys Objet500 Connex. Afterwards, almost all fabricated data sets described in Chapter 5 (“Voxel-Printing for Data Fabrication”) were processed in one print job with the herein introduced data fabrication framework on a Stratsys J750 printer (Figure 33). This highly parallel workflow highlights the ability of this framework to simultaneously process and fabricate multiple and unique data sets, consisting of many million point and line elements, large volumes, and gigabytes of image stacks. Furthermore, instead of introducing a completely new data format, CAD design metaphor or fabrication method, this data processing approach efficiently unifies established scientific data formats with well-engineered, commercially available additive manufacturing technologies. The introduced voxel-based fabrication framework allows leveraging the hardware capabilities of state of the art multi-material 3D printers, which is still widely unutilized. By bridging the gap between data and matter through voxel-based 3D printing, the framework could support the mediation of information from the physical world (data acquisition), to the digital world (data processing and CAD) and back to the physical world (additive manufacturing). Enabling a design process across scales and disciplines, our approach can leverage new synergies that will lead to improved or completely new applications in education, medicine, and the biological, physical, and social sciences.
7 REFERENCES


