For most of human history, maps have illustrated the locations of cities, roads, and other geographic features on 2D paper. Other representations display the Earth on a spinning globe. These physical models let users interact with a physical Earth, understand the relative distances between locations, and explore the geographic properties of regions.

With the emergence of new technologies for capturing geospatial datasets, however, our information about the Earth has expanded beyond simple name tags, major roads, and political boundaries. Web maps such as Google Maps provide geospatial dataset visualizations using computer-generated 2D maps. These maps may utilize different resolutions and multiple layers of data (such as roads and satellite images). Yet, various types of geospatial datasets are hard to visualize, and because of the mapping distortion between spherical/ellipsoidal domains and (Euclidean) 2D domains, misinterpretations of areas and distances are common.

Digital Earth and virtual globes (such as Google Earth) have been proposed to overcome the 2D map issues. Digital Earth is a 3D representation that integrates various geospatial datasets and with which we can interact to retrieve information related to a particular region. Even though analysis and data integration are important components in Digital Earth, computer-generated models still suffer from comprehension problems caused by projecting 3D scenes onto 2D screens.

Physical models are alternate solution that can support better geospatial dataset visualization. A large physical 3D model can help users to better understand complicated datasets through physical interaction. A variety of techniques exist for producing paper-craft models of the Earth, but we propose using durable physical 3D models produced via digital fabrication. Such models are solid and stable enough that they can allow different 2D and 3D data layer attachment in order to physically display geospatial datasets.

To help users understand the geospatial datasets of different regions and resolutions, such a physical model should be scalable, with pieces that can be attached to each other to cover larger regions. Not only is the final physical 3D model of the Earth useful as a tangible learning tool, but the process of creating such a model is also beneficial to the learning process. Therefore, the process of creating the physical 3D model should be affordable and repeatable.

Combining the technologies available in geospatial modeling and visualization with recent advances in fabrication and 3D printing provides a useful means of better conveying complicated geospatial concepts. In this article, we explain the benefits of using affordable 3D printing technologies to make scalable physical models that can visualize various geospatial datasets. To ensure the research is repeatable, affordable, and useful, we focus on several goals. The physical model of the Earth (base) should be able to hold multiple geospatial datasets and should be scalable (large or small). We should be able to fabricate datasets at different resolutions for the physical models. Finally, the 3D printer should be affordable (single color and small).

To fulfill these goals, we combine digital fabrication with a discrete global grid system (DGGS)
Computational Design and Fabrication

Figure 1. Physical 3D models. (a) Our physical 3D model divides the Earth into hierarchical cells, which we use to define the printable pieces. Datasets with different styles can then be attached to the physical model, such as (b) a 3D printed layer that visualizes the populations of different countries or (c) a transparent analytical data layer. (d) Our method can produce models at different scales.

to provide a useful tool for visualizing multi-resolution geospatial datasets. We also provide a mechanism to print and attach a set of printable segments to produce a scalable model of the Earth. Furthermore, we discuss some possible interactions and visualization techniques for this 3D physical model.

To create our physical 3D models, similar to Digital Earth, we first break down the Earth into printable pieces so it is possible to retrieve geospatial datasets and connect them easily. We define this discretization in a hierarchical manner to enable the use of multiresolution datasets, if needed. For this purpose, we use a DGGS that divides the Earth into hierarchical cells on which geospatial datasets can be assigned. These cells are indexed using a hierarchical mechanism: the index of a parent cell is the prefix of its children. We use the DGGS cells to define the printable pieces (which can be connected together using our provided connectors) and to determine which datasets can be attached to them. In this way, datasets at appropriate resolutions may be retrieved from the DGGS cells and attached to the printed pieces (see Figure 1).

Geospatial Physical Fabrication

Here, we first describe the works related to Digital Earth and geospatial visualization. We also outline digital fabrication techniques and the ways in which different datasets can be visualized using 3D printers.

Digital Earth and Geospatial Visualization

As data-capturing technologies continue to advance (including satellite imaging, crowd-based surveying, and geotagging), we are constantly capturing ever larger amounts of geospatial data that can be used to address important challenges related to the Earth. However, this immense, multiscale, and diverse data needs to be processed and integrated into a common domain to harness this potential, with support from a system for visualizing and analyzing geospatial queries. One such a system is Digital Earth, a 3D digital representation of the Earth used as a reference model for the integration, management, visualization, and processing of geospatial data. The most common approach to Digital Earth divides the Earth into highly regular cells (a DGGS), to which data are assigned.

In a DGGS, a simple polyhedron is used to coarsely approximate the Earth. The faces of the polyhedron are refined and projected onto the sphere to generate spherical cells that distinctly represent the Earth’s surface. This lets us assign data to different locations and establishes a multiresolution representation of the Earth with mostly uniform cells. An indexing system is used to assign and retrieve geospatial datasets.

Digital Earth provides a framework to visualize, analyze, and combine various types of datasets. Geospatial imagery datasets (such as aerial or satellite photographs) are often used to texture the cells. Elevation data, usually offered as digital elevation models, are used to represent a region’s height or elevation. Another important type of data in Digital Earth, vector datasets, are defined by collections of points, polylines, and polygons that are used to outline political boundaries, rivers, roads, and so forth.

Physical Data Visualization

A physical data visualization is a physical model that encodes data into its geometry and helps users understand and explore data. Recent advances in digital fabrication and tangible interfaces have opened up various research possibilities in this field. Examples of physical visualizations of geospatial datasets include spinning globes, terrain models, prism maps, and interactive displays (see dataphys.org/list/tag/cartographic). Compared with virtual models, physical visualizations can be handled and controlled more easily, can improve users’ cognition, and allow for more natural user interaction. One user study showed that a 3D physical visualization improved the efficiency of users’ information retrieval.
Other research in the physical data visualization field has explored its benefits over digital-only models. One study noted that even nonexperts in information visualization can propose their own visual representations of a specific dataset through the tangible environment provided by a physical visualization. Another work integrated the physical visualization workflow from data filtering using physical fabrication. In that system, users can create their own physical visualization of their desired data. Physically dynamic bar charts and other interactions that support fundamental visualization tasks (such as annotation and navigation) have also been used for data visualization.

We propose a physical visualization of geospatial datasets that lets users choose and combine different datasets and does not limit them to a specific predefined visualization or data type. Our method allows dynamic physical models to be produced via a facilitated assembly process that provides the user with interaction possibilities.

**Digital Fabrication and 3D Printing**

One of the oldest and most accessible physical visualizations of geospatial datasets is the spinning globe. These globes use interrupted maps, which are cut along chosen curves and folded to cover the sphere. The most common method of creating a paper-craft globe is a gore map that uses Apian’s first projection (www.progonos.com/furuti/MapProj/Normal/ProjInt/projInt.html). This is a non-equal-area projection, but its geometry can be built using a ruler and a pair of compasses. We can make a paper globe by printing this map on a piece of paper, cutting it by hand, and sticking its gores together (www.korthalsaltes.com/model .php?name_en=globe). Another approach to making a globe uses folded papers. In this method, polyhedral globes are formed from an unrolled 2D pattern of the polyhedron (www.progonos.com/ furuti/MapProj/CartIndex/cartIndex.html).

Although these paper-craft models are relatively easy to fabricate, they are not durable or strong enough to interact with, and we cannot produce a scalable paper craft capable of holding multiple datasets. Well-designed fabricated 3D objects can address each of these issues.

Specifically, 3D printing lets us produce a physical model regardless of its complexity. 3D printing can positively impact education, both as a means of learning and as a method of designing and creating educational tools. One study used open source 3D printing for experimental educational scenarios by giving the students the chance to use 3D design software packages and to print their designs later on. In another study, medical students used a 3D printed physical hepatic segment model.

There have also been efforts to overcome the shortcomings of affordable 3D prints, such as a lack of color or materials and the limited size of the printed objects. An efficient system was introduced to segment a model into printable pieces that could be connected together later on. Researchers have also segmented a 3D model into printable pieces that they later connected to a base made of an alternative material (such as wood) to reduce costs and material usage. To overcome color and material limitations, a 3D model was segmented into flat pieces, and a guide was provided to attach any material with any color to the 3D print. An intermediate domain such as water or plastic on which the desired texture can be printed has been used to paste the texture on the 3D print.

Because one of the stated goals of our research is accessibility by way of affordable 3D printers, we have come up with a design solution that addresses these size and color limitations. All DGGSs already provide a segmentation of the Earth into a set of cells, so we use it to segment the Earth into printable pieces. To assign colorful datasets, we use additional layers that can be attached to the printed model.

**Methodology**

Geospatial datasets are available from different sources and frameworks, and the most well-known and accessible are Digital Earth datasets, which are available at different resolutions. Our application uses a DGGS because it offers several characteristics that are compatible with our needs.

In a DGGS, the Earth’s surface is divided into a set of distinct cells that result from projecting the faces of a refined polyhedron onto a sphere. Beginning with a simple polyhedron that approximates the Earth, the faces of the polyhedron are refined to a desired resolution and a hierarchy is established between the faces at consecutive resolutions. Different types of projections (usually area preserving) are then used to map the refined faces to spherical cells on the globe (see Figure 2). These cells are then used to organize datasets, and unique indices indicate each cell’s resolution and geospatial location. These indices also indicate how the cells are connected to each other. Appropriate datasets can be retrieved from a geospatial database and attached to the cells using the indexing system.

DGGS offers important benefits for our application. First, the Earth is divided into a set of distinct cells, which provides a natural and meaningful
Computational Design and Fabrication

segmentation of the Earth model into units for fabrication in a modular manner. Using appropriate connectors, the printed units can be assembled and extended to create a scalable Earth model. Second, the multiresolution representation lets us build a physical model at the desired scale with any associated dataset. Third, geospatial datasets are organized according to the cells, so we can easily use these cells to retrieve the data associated with each cell (printable unit). Fourth, using each cell’s unique index, we can determine how the printable units connect to each other.

Our approach uses an equal area icosahedral DGGS discretized into mainly hexagonal cells. The base model is a truncated icosahedron with 12 hexagonal and 10 pentagonal cells, prized for approximating the Earth with low distortion. This representation is compatible with the PYXIS WorldView platform (www.pyxisinnovation.com), which provides a variety of geospatial datasets. The truncated icosahedron’s cells define the coarsest physical model of the Earth, and the diamonds are used as printable units of the high-resolution datasets. The DGGS we used is an efficient representation for analyzing and visualizing geospatial datasets because it employs an equal area projection. However, we could use other types of DGGSs if we wanted to emphasize other aspects of the dataset. For instance, to visualize information related to navigation, a DGGS with a conformal projection might be a better choice.

Physical Modeling

We fabricated two physical models at different scales. The first is a coarse print representing the entire Earth on a small scale, modeled as a truncated icosahedron (world globe). The second is a curved print of Western Canada (curved model). To fabricate the models, we used a MakerGear M2 single extruder printer. This is an affordable 3D printer capable of printing models with dimensions up to 200 mm × 250 mm × 200 mm.

Polyhedron Globe

For a simple physical visualization of geospatial datasets, we use the base polyhedron of the selected DGGS (truncated icosahedron in our approximation) as the world globe. Representing the Earth via simple polyhedrons or paper crafts is common, and the benefits include the ability to cover them with low distortion maps. The fabrication process for the base globe and its associated datasets is easy and can be repeated for educational purposes.

We decomposed the model into a set of separate printable pieces. In this case, the 32 faces of the truncated icosahedron (20 hexagons and 12 pentagons) were a natural choice. As a result of the
printing size limits and the final model’s scale, we printed two hexagons or three pentagons in each printing session. The printing time took about 3.5 hours using a 20 percent infill, and each printing session consumed about 80 grams (gr) of filament.

Because the cells are printed separately, we need a mechanism to connect them together into a single stable model. Because of the thickness of each piece, we taper the pieces by 45 degrees so that the pieces fit together (see Figure 3a). In addition, we use a set of connectors to hold the pieces together. For this simple model, we designed connectors using the exact angles between neighboring cells in the truncated icosahedron (138 degrees, 11 minutes for hexagon-hexagon attachments and 142 degrees, 37 minutes for hexagon-pentagon attachments) (see Figure 3b). One kilogram of white PLA filament was used to print all 32 faces and the required connectors.

This polyhedron provides a rough estimation of the Earth and illustrates which portions of the Earth correspond to which DGGS cells at the coarsest resolution. In addition, this model can be viewed from different angles and does not need an additional support stand. Such a physical model can be used to illustrate datasets associated at a coarse resolution. For instance, Figure 1b illustrates the world political boundaries attached on the polyhedron globe.

**Curved Globe**

The simple base model can be used to illustrate datasets at a coarse level, but it has two main limitations. It is piece-wise flat and is also too small to visualize higher-resolution datasets; the maximum size of each piece is limited by the printer’s size. For smaller areas of interest, it would be beneficial to have larger-scale models of the Earth and higher-resolution datasets. Thus, we designed a larger-scale model of the Earth with curved cells. Using a DGGS makes this possible and allows us to print only a portion of a potentially large Earth model. The printed portion of the globe can encompass any region or country desired. As a proof of concept, we visualize the western part of Canada, including British Columbia, Alberta, Saskatchewan, and part of Manitoba (see Figure 4). We use resolution three of the PYXIS DGGS to select printable cells for this area.

In the underlying PYXIS WorldView structure, cells can be packed and transformed into diamond-like meshes. These diamonds are curved meshes (Figure 4b) obtained using the dual conversion between hexagons and triangles. Our region of interest (Western Canada) at resolution three encompasses 16 diamond, each covering roughly 10 million square meters. To make a physical model associated with this region, we need to determine an appropriate size and connecting technique for
the diamonds. A globe diameter of 2 meters provides an appropriate scale for the region of interest and its corresponding datasets, so we size the printable diamonds to achieve this scale (Figure 4c). The DGGS provides different geometries for each diamond. In other words, diamonds follow the geometry provided by the DGGS. Therefore, we need a reference system in order to attach them once they are printed. To this end, we use the chosen DGGS’s indices as a reference to connect the diamonds together by engraving the index of each diamond on its back (Figure 5a). The indexing used in our DGGS is a hierarchy-based indexing system with numbers in base nine.6

To ensure the partial globe is modular and scalable, we must be able to add new regions to the old ones. To make each piece attachable and detachable, we designed a supporting wall (1 cm thick) at the edges of each diamond into which three female connectors are carved on each wall (see Figure 5b). To connect these diamonds, we designed separate male connectors (2 cm long) that can fit tightly in the female connectors (see Figure 5c).

To ensure a proper fit and an appropriate thickness, we modeled three different connectors via offsetting from the female connectors by multiples of 0.1 mm (0.1, 0.2, and 0.3 mm offset). After testing the printed male connectors, the best grip was obtained using a 0.1 mm offset from the female connectors. The infill amount also plays an important role here; our results showed that the fabricated connectors using a 20 percent infill were more likely to break during the assembly process. As a result, we found it best to use infill amounts of 50 percent or more.

We fabricated each of the 16 diamonds in our curved model of Western Canada using 20 percent infill structure in approximately 4 hours and 45 minutes. Each printing session consumes about 120 gr of the filament. For all 16 diamonds and connectors, we used two kg of white PLA filament. Because the model is curved, we need a stand to hold the structure (Figure 5d). We designed the stand to hold the edges of the four diamonds that meet in the middle of the curved model. To achieve this, we designed the top of the stand with a cross-shaped depression into which we place the intersection of the four diamonds. Once all the parts have been fabricated, it takes about 30 minutes to assemble the physical model.

We use the physical model of the partial Earth as a base for attaching geospatial datasets. This model can also provide a physical visualization of geospatial datasets.

Data Visualization

As we have discussed, our ultimate goal is to make a model that allows us to visualize different types of datasets. A pin-hole design lets us attach and detach physical layers for these datasets to the base models. Because each piece of the model should be able to hold the corresponding piece of the dataset, we designed some connecting pins on the surface of each printed cell to hold physical data layers (see Figure 6).
The pin-hole mechanism allows us to attach multiple layers onto the physical globe (see Figure 6d). These layers can be printed on paper (opaque or transparent) or as a 3D print. Based on the base globe’s characteristics, the nature of the dataset, and the visualization method, we can use various layering methods.

Figures 1b and 1c show the use of multiple data layers on the world globe (the truncated icosahedron). In Figure 1c, the first layer is an opaque layer printed on photo paper visualizing world political boundaries. To illustrate a 3D visualization, we attached a 3D printed layer that visualizes the populations of different countries in Europe onto one of the cells (see Figure 1b). In this example, each country’s population is proportionally mapped to its height. To fabricate this physical layer, we triangulated each country’s boundary and extruded the resulting 2D mesh based on each country’s height with a closed smooth B-spline curve. In addition, we attached a transparent layer to illustrate the possibility of visualizing another analytical data set (such as each country’s energy use) atop the cell (see Figure 1c).

To create cell-based data layers, we can use the same DGGS as the base model. We initially import any desired datasets into a DGGS (such as the PYXIS WorldView). Afterward, we retrieve the data associated with one or more printable units at specific resolutions. Using the DGGS, we export the geometry (mesh) of the desired cells and their data-associated layers. Because each cell’s geometry is not necessarily flat, we map the data associated to a 2D domain such that, after printing, this 2D domain can be mapped to these cells. In our case, the only curved cells are diamonds, for which we use an orthogonal projection after finding the plane that best fits the four corners of the diamond. More complex projections or parametrizations such as ABF (Angle Based Flattening) can be used when the curvature of the cells is high. However, because these diamonds are small pieces of a sphere with relatively low curvature, such a mapping produces fairly good results (see Figure 7).

Additional Examples

Now that we can map datasets on printable and attachable 2D pieces, we can produce various visualizations for our physical model. As an example, Figure 7 shows paper layers attached to Western Canada. These paper layers include an elevation dataset, a Canadian National Fire data set, and a combination of the two.

Using fabricated 3D layers provides us with a unique opportunity for creative visualization of geospatial datasets. For instance, because elevation data can be better visualized in 3D, we can use a physical layer for this dataset. We have used PYXIS WorldView to retrieve the elevation data associated with one of the diamond cells (see Figures 8a).

To compare datasets of different regions, we can visualize different statistical datasets related to our region of interest. Figure 8b shows a 3D printed pie chart that illustrates the number of different tree types found in its corresponding diamond. The bar chart in Figure 1d also illustrates the populations of different regions. These 3D printed charts can be combined with different paper layers, for instance by making cuts on the paper layer and placing it on top of the 3D printed charts (Figure 1d). To do so, the 3D chart models are projected onto a flat 2D diamond under the same orthogonal projection used to make paper layers. The resulting flat 2D diamond provides the exact locations of the cuts to be made. This can be
done using either a desktop silhouette cutting machine or a laser cutter. By subtracting these pieces, the printed paper easily fits over the 3D printed chart and can be attached to the globe using pins.

To make our models more interactive, we can attach a transparent layer to the diamonds that users can sketch on in decision-making and design processes. Adding pins to different parts of the partial globe is another interactive use of this model. By adding pins to the region of interest, we can see the relative distances between multiple regions and compare their associated datasets. Figure 9 illustrates such interactive possibilities.

The physical Earth models we describe here, which were produced without the need for complicated manufacturing techniques, work hand in hand with any type of geospatial dataset. Different data visualization techniques also let us attach various datasets onto the globe as layers, giving users the chance to analyze and study datasets as needed.

In the future, to improve and extend this work, we can make visualization methods more creative by designing more functionality for the globe-scale model. A good example could be the use of LED lights on the surface model to visualize different types of dynamic datasets.

We intend to use these visualization techniques in practical applications, such as education, and evaluate our techniques in conveying geospatial concepts. For this, we may use higher resolutions to illustrate the details needed for urban projects. Urban planners, urban designers, and even architects could use our models as a basis for making design decisions and to present their results to clients. Thus, we plan to perform a set of formal user studies to evaluate our proposed method and its potential applications to education, urban planning, urban design, and architecture.

Figure 8. Creative visualization of geospatial datasets: (a) a sample diamond containing a 3D printed elevation dataset and (b) a pie chart printed on the partial curved globe model.

Figure 9. Interacting with models. (a) Users can make sketches directly on the globe’s surface or (b) add pins to the globe and use them to show vector datasets.

References

Hessam Djavaherpour is a PhD student in computational media design at the University of Calgary. His research interests include responsive architecture, dynamic structures, digital fabrication, 3D printing, physical visualization, and data-centric design approaches. Djavaherpour has an MS in architecture from the Iran University of Science and Technology. Contact him at Hessam.djavaherpour@ucalgary.ca.

Ali Mahdavi-Amiri is a Natural Sciences and Engineering Research Council of Canada (NSERC) postdoctoral fellow at Simon Fraser University. His research interests include computer graphics, geometric modeling, and 3D fabrication. Mahdavi-Amiri has a PhD in computer science from the University of Calgary. Contact him at a.mahdavi.amiri@gmail.com.

Faramarz F. Samavati is a full professor in the Department of Computer Science at the University of Calgary. His research interests include computer graphics, visualization, 3D imaging, and geometric modeling. He has received the Digital Alberta Award for Best in Cross-Platform Content, a Great Supervisor Award, and the University of Calgary Peak Scholar Award. Samavati has a PhD in mathematical sciences from Sharif University of Technology. Contact him at samavati@ucalgary.ca.