

# Display Blocks: Cubic Displays for Multi-Perspective Visualizations

by

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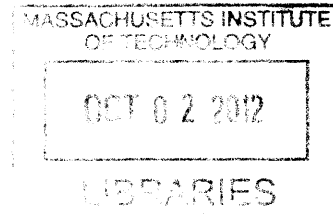
Submitted to the Program in Media Arts and Sciences,  
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## ABSTRACT

This thesis details the design, execution and evaluation of a new type of display technology, known as Display Blocks. Display Blocks are a response to two major limitations of current displays: visualization and interaction. Each device consist of six organic light emitting diode screens, arranged in a cubic form factor. I explore the possibilities that this type of display holds for data visualization, manipulation and exploration. To this end, I also propose a series of accompanying applications that leverage the design of the displays. To begin assessing the potential of this platform and to define future directions in which to expand this research, I report on a series of interviews I conducted regarding the potential of Display Blocks with relevant technologists, interaction designers, data visualizers and educators. The work encompassed in this thesis shows the promise of display technologies which use their form factor as a cue to understanding their content.

Thesis Supervisor: Pattie Maes, PhD  
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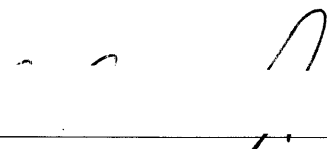
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The following people served as readers for this thesis:

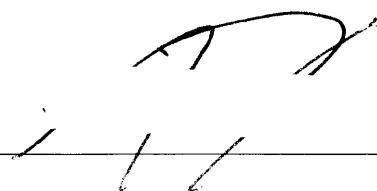
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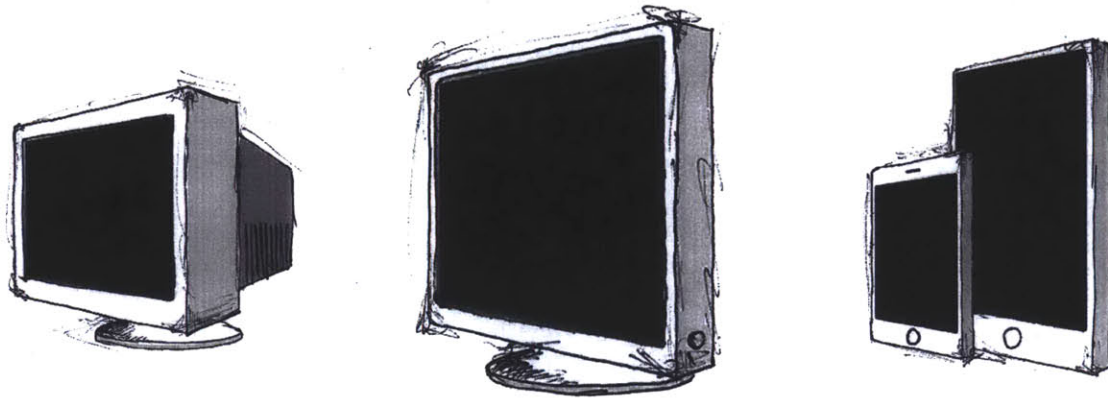
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# INTRODUCTION: OF SCREENS AND OBJECTS

Screens are everywhere. Sitting at a café table, one might have at least three screens within peripheral view - perhaps a laptop and a cellphone side by side on the table, and a television screen in the background. These screens were designed to support technologies such as cinema and television and were later used in computing contexts as well, including computers, cellphones, and tablets. As screens have become more portable and interactive, they have also colonized traditional media, such as books and newspapers. At the same time, screens have permeated a variety of fields, ranging from medicine to retail. Surprisingly, throughout this process, the fundamental shape of screens has not changed much: they continue to be rectangular and flat. As screen technologies become increasingly widespread, designers should evaluate the validity of current form factors and explore new possible shapes and configurations.





▲ Evolution of computer displays. From cathodic ray tube (CRT) to light emitting diode (LED) to tablet and mobile devices.



▲ The window metaphor has remained the same for all of these devices.

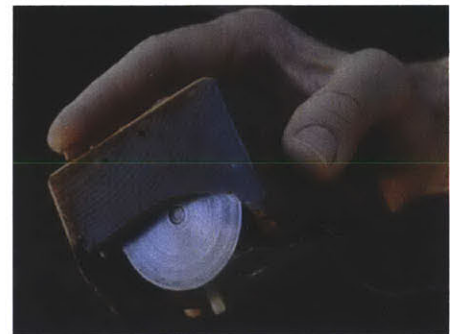
Because of their shape and use, we might think of screens as windows to other worlds – whether the cinematic narrative of a movie or our finances on a spreadsheet. This metaphor has proven to be a powerful one. It originated with cinema and was later applied to television; most recently, it was successfully adopted in computing as well. In all of these cases, the window metaphor has shaped the way we consume information and, consequently, the delivery of information, the interfaces we use to manage information, and, ultimately, information itself. As computing permeates our lives in new ways, this metaphor is applied without challenging its suitability for these new purposes.

Cinema and television are passive media – we sit and watch – on the other hand, computation is an active medium, which requires us to interact. The adoption of screens as the main visual representation for computation meant that computation became a decoupled medium. That is, the first computer established a divide between its manipulation – or input – and its representation – or output.



While screens became something that we solely look into, we had to interact with content by means of other objects such as keyboard and mouse. More recently, developments in multi-touch technologies and gestural interfaces have introduced some direct manipulation to minimize this disconnect. However, the resulting interactions, although more natural and intuitive, are still far from the rich ways we might manipulate and relate to objects in our environment. One of the major challenges of interaction design has been to bridge the gap between input and output to finally make them converge, thereby combining manipulation and representation in a single object.

We can try to achieve this convergence from either of two sides: designing more natural and integrated input technologies or experimenting with different, more familiar form factors for output. The dominant approach in human-computer interaction has been to focus on the first of these, aiming to create more natural ways for input. Beginning with the first television remote controls, moving to more complex devices like the mouse and keyboard and, more recently, multi-touch technologies, tangible interfaces and gestural recognition; these technologies continue to revolutionize the ways we manipulate digital information. While it is easy to observe a trend of more intuitive and easy-to-master inputs, there is not an equivalent occurrence of this trend in terms of output. Throughout this time, our primary means of output has remained the same: the planar screen. In other words, while form factors for input have come a long way, the form factor of the screen itself has not.



▲ First mouse invented by Doug Engelbart in 1963.



▲ Zenith Radio Corporation invented the first remote control in 1950.





▲ Cave paintings in Lascaux. Arguably one of the first examples of representation and storage of information in a flat surface.



▲ Type carriage for a press printer. This type of printer is a descendent of the first Gutenberg printer and was the standard until inkjet printers became available.



▲ New York Times edition for the iPad.

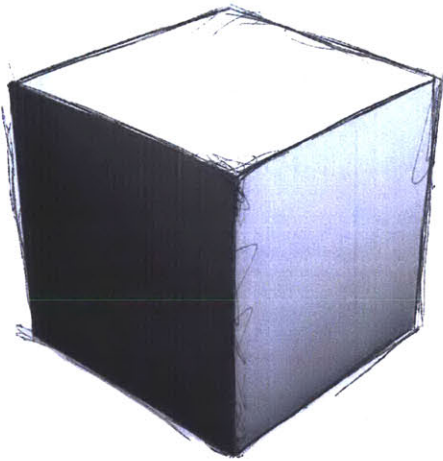
We are accustomed to consuming and storing information, mostly, on rectangular flat surfaces. Arguably, this way of consuming and storing information goes back to ancestral cave paintings and has since evolved from parchment, into print and, later, the screen. In parallel to this evolution, the amount and variety of accessible information has grown exponentially, to the point that there is data too complex to visualize and so much of it that we cannot possibly consume it in lifetime. In response to this phenomenon, new tools have been developed to represent complex information in flat displays - like the case of three-dimensional computer graphics - and information visualization techniques have evolved to enable navigation of large amounts of data. Once more, this is an asymmetric evolution: while techniques have been developed to more efficiently fit data in current display surfaces, the surfaces themselves remained essentially the same in terms of shape - flat and rectangular.

The work contained in this thesis lays the foundation for designing alternative output technologies that tackle several limitations of current displays. It does so by identifying these limitations and conceptualizing, designing and building an alternative display technology: Display Blocks. Display Blocks are a collection of cubic displays that are easy to manipulate and interact with and which support new types of visualization. They bridge the gap between physical and digital from an output design perspective and, at the same time, expand the visualization possibilities through their volumetric nature. The design is not intended to be substitutive of current display technologies; instead, it seeks





to expand the palette of display technologies for visualizing computation in different ways. It is my hope that this work will inspire others to explore more of these limitations, and to enrich interfaces - not only from the input perspective but also by thinking about output as a design variable.



◀ One of the initial sketches for the Display Blocks concept.





# TWO LIMITATIONS OF CURRENT DISPLAYS

As discussed in the introductory chapter, display technologies have remained the same for a long time. While research has tried to improve the way that we visualize information and our means of interaction with these visualizations, there has been minimal exploration of new form factors that could better adapt to content. In this chapter, I discuss in detail the two main limitations of current display technologies that informed the design of Display Blocks: visualization and interaction.



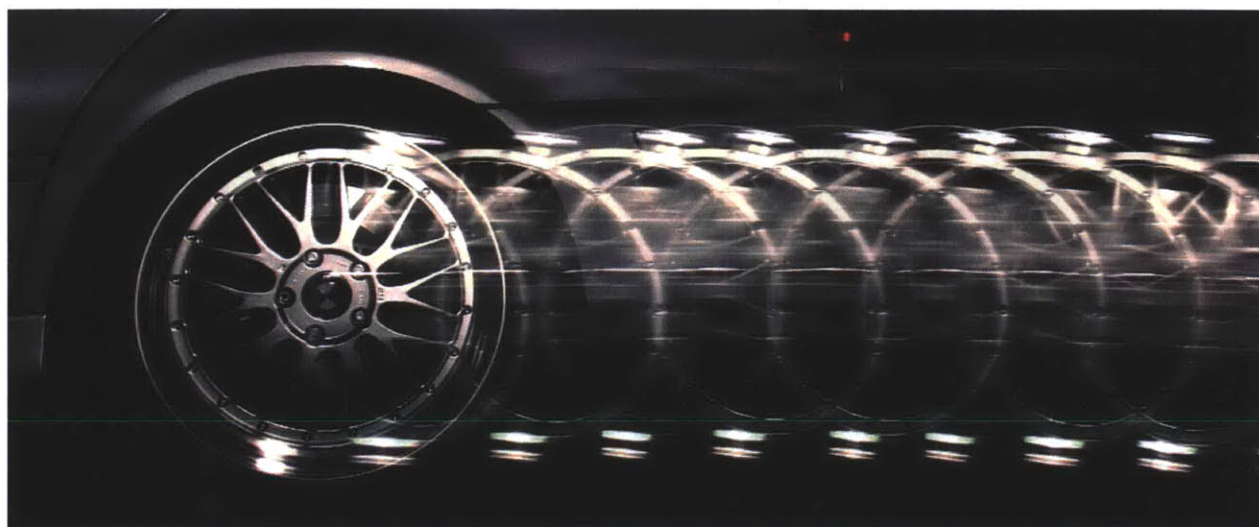
## 1. VISUALIZATION

There is only so much that a flat display can represent. A plane has two dimensions, and, therefore, any representation whose object exceeds this amount will need to be simplified. For instance, when we watch a movie, we see frames one after another. Each individual frame is two dimensional, but they play in a sequence; hence their third dimension is time. Another example is a multi-camera security system whose various security feeds are arranged in a grid. In both of these cases, we are losing information. In the case of the movie, we are losing the reference to the previous frame - because we can only see one frame at a time. In the case of the security system, we are compressing each image, limiting the resolution for each of the individual security feeds.

This dimensional simplification is not necessarily undesirable; for instance, it enables filmmakers to use cuts that transition between scenes in order to establish narratives. However, such simplification can be hindering as well. Consider the case of the movie, dimensional simplification would make it harder to infer the acceleration of a tea cup being dropped to the floor - precisely because we are losing the contextual information that the previous frames would provide. Of course, most movie goers are not interested in the acceleration of the objects appearing in a movie, but in a classroom environment this can be a tipping point for students to understand physics.



We perceive our environment in three dimensions, four if we include time. Despite having ways to accurately represent information up to the third dimension, mainstream technologies have always limited us to only two.



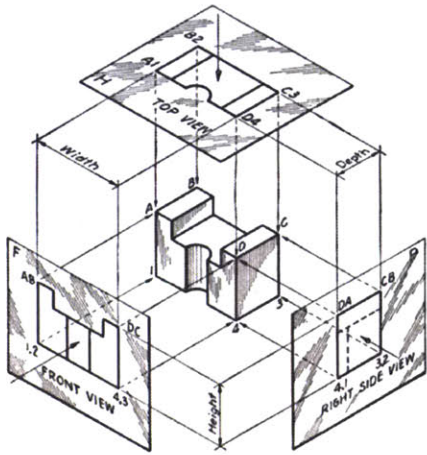
▲ The aggregation of frames enables the visualization of acceleration.

When we want to draw an object onto a piece of paper, the first thing we need to do is decide from which angle we are going to capture the object. By choosing one perspective, we not only lose the occluded side of the object, but also any other angle of vision that we could have. Cubism explored this limitation; artists such as Pablo Picasso played with decomposing objects that seem to unfold to reveal their most interesting perspectives. Taking a more pragmatic approach, we could draw multiple perspectives of an object on different parts of our canvas. Even by doing this, the resulting ensemble of drawings will only give us a better understanding of the object if we have pre-negotiated





▲ Guitar (I love Eva) - Pablo Picasso (1912). An example of cubism and how it exposes multiple perspectives of an object at once.



▲ Orthographic perspectives are different representations of the same objects in increments of ninety degrees.

a shared interpretation of their spatial relationships. One instance of this type of convention is blueprint schematic drawings; they define different orthographic views – front, back, left, right, top and bottom – and arrange them in a specific way so that they can be understood by others. Finally, if we draw each possible perspective of an object on a different piece of paper, we could create an animation that would show the object spinning in place. As in the example of the movie, we would be losing contextual reference, as we can only see one perspective at a time.

As we can see, the process of representing three-dimensional objects on flat surfaces generates a certain ambiguity. If we decide to represent an object from only one perspective, we harbor ambiguity about the hidden part; if we decide to draw all possible perspectives, we require disambiguation to understand the relationship between these perspectives; if we create an animation out of all the different perspectives, we lose contextual reference for each one of them.

Many disciplines have devised ways of representing domain-specific three-dimensional data. For example, architects build physical models to better understand how a project will look once it is built. Similarly, chemists physically construct complex molecules to better understand their composition. With the advent of three-dimensional graphics in the late 1970s, it became possible to model some of these processes with computers. Because computer screens could refresh at a high speed and computers could take user



input, these technologies were able not only to represent objects from all imaginable angles, but they also allowed us to interactively explore them. Current computer-aided design (CAD) software uses similar ways of representing objects. These types of software usually offer two possible configurations: a unique interactive perspective of the object or a layout with four smaller views - three fixed orthographic and an interactive arbitrary one. We can see that screens are facing the same disambiguation problems that we might have when drawing an object on a piece of paper; we can either show one unique perspective of an object or show several smaller representations from different angles.

The significant advantage of visualizing three dimensional objects with a computer is that we can interact with the objects in real time. We can rotate, zoom and pan as we navigate a three-dimensional scene. However, the majority of computer applications were designed to work in two dimensions - allowing for pan and zoom only. As a result, the ambiguity gets translated, in the case of a computer, to the interaction devices we use for navigating three-dimensional worlds. Currently, the best compromise for disambiguating this sort of interaction is to use keyboard and mouse combinations that are cumbersome and unintuitive.

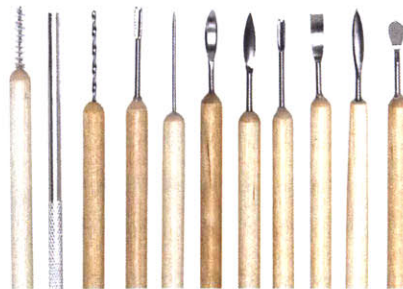
There is extensive research into disambiguating navigation of virtual three-dimensional objects; this encompasses new tools for interacting, new ways of navigating, and new types of displays. Since the focus of



this thesis is display design, my interest is to focus on the third of these. One of the best ways to represent three-dimensional objects is to have a three-dimensional display. Because these technologies offer the possibility to visualize objects in three dimensions, they solve all of the ambiguity problems described above. However, they can only visualize volumetric data; they cannot visualize, for instance, the relationship between frames of a movie in terms of time and space.

One of the objectives of this thesis is to design a type of display that can visualize multiple perspectives - a display that solves the ambiguity problems resulting from dimensionality compression and that is also versatile enough to be used with many types of data. By developing such a display, I am not trying to disregard current display technologies; rather, I seek to expand the ecology of these devices. I envision a future in which, when we want to visualize any type of data, there is an appropriate type of display for doing so. Display Blocks are intended to contribute to this selection of data visualization tools by exploring how displays can more accurately represent any kind of multi-perspective data.

► Craftsmen use different tools for different tasks. Similarly, we might want to use different types of displays for visualizing different types of data.





## 2. INTERACTION

In addition to being limited in terms of data representation, the flat nature of displays affects the way we perceive them as objects. Returning to the window metaphor, windows are used in a very specific way: we look through windows, rather than manipulating them. Because of this, screens are well-suited for passive media. On the other hand, when we try to use screens in an active medium such as computing, most setups still require external controls such as the keyboard and the mouse for interacting with content. This division between content - the screen - and manipulation - keyboard and mouse - divorces input and output functionality, yielding a decoupled experience. In some cases, this divide is necessary or preferable - i.e. when we type documents the field of the keys under our fingers enables us to type without looking. In other cases, however, it can constrain the potential for more intuitive interactions with data.

Let us consider early personal computers; they were meant to be work stations on a desk and were complemented by a screen, a keyboard and a mouse. This configuration heavily relies on the window metaphor, as the screen is a rectangular, flat and immovable gateway to the digital. Computers lost the constraint of immobility as we transitioned to laptops. From a user point of view, with the arrival of laptop computers, the metaphor remained unaltered; the screen was still meant solely for information consumption and required the use of the same external



devices for interaction. This new form factor, however, brought with it an interesting functional detail: we could fold laptops closed to turn them off. Closing an object – i.e. a book – is a common way to signal that we are done using it. This feature begins to weaken the window metaphor by appealing to the physicality of the screen, and its shared nature with other objects around us.

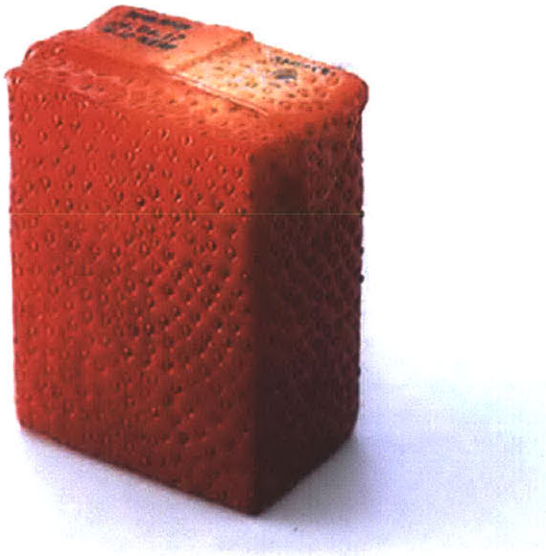


▲ Evolution of screen-based computing devices. Over the years the screen has accumulated more and more characteristics of other objects, challenging the window metaphor.

More recently, touchscreens, widely found in phones and tablets, have incorporated a variety of sensing capabilities that have enabled devices to be aware of how they are manipulated. These improvements have started to bridge the previous divide between physical and digital in computing devices. The most prominent of these sensing capabilities are multi-touch surfaces. By allowing users to manipulate content with their fingertips, these devices collocate input and output. Other sensor technologies further enhance the richness of interactions by allowing access to device-relative data, such as orientation and geolocation. This new generation of devices defies the window metaphor; however, it is still built on top of it. While we are able to interact with the content in a richer way, this content is still framed in a flat rectangular surface.

The next frontier is to modify the shape of display technology. The shape of an object tells us a lot about the object itself. If we take a knife, for example, we know immediately where to grasp it; it almost describes, with its shape, how it is supposed to be used. Similarly, display technologies could make their use apparent through their

shape. Instead of building interaction on top of existing display technologies, we should strive to create displays that inform us of their use and content. This is, of course, an ambitious and long-term goal; however, we can begin by experimenting with basic shapes before later extrapolating to more complex ones. Display Blocks is one such attempt at creating a differently shaped display along with several types of content that might be more graspable with it.



◀ In the case of this packaging by Naoto Fukasawa, the container describes the content. Can we design screens that help us understand their content?

*“Can we create different types of displays for visualizing different types of data? Can we design screens that, as objects, provide cues to interpret and manipulate their content?”*

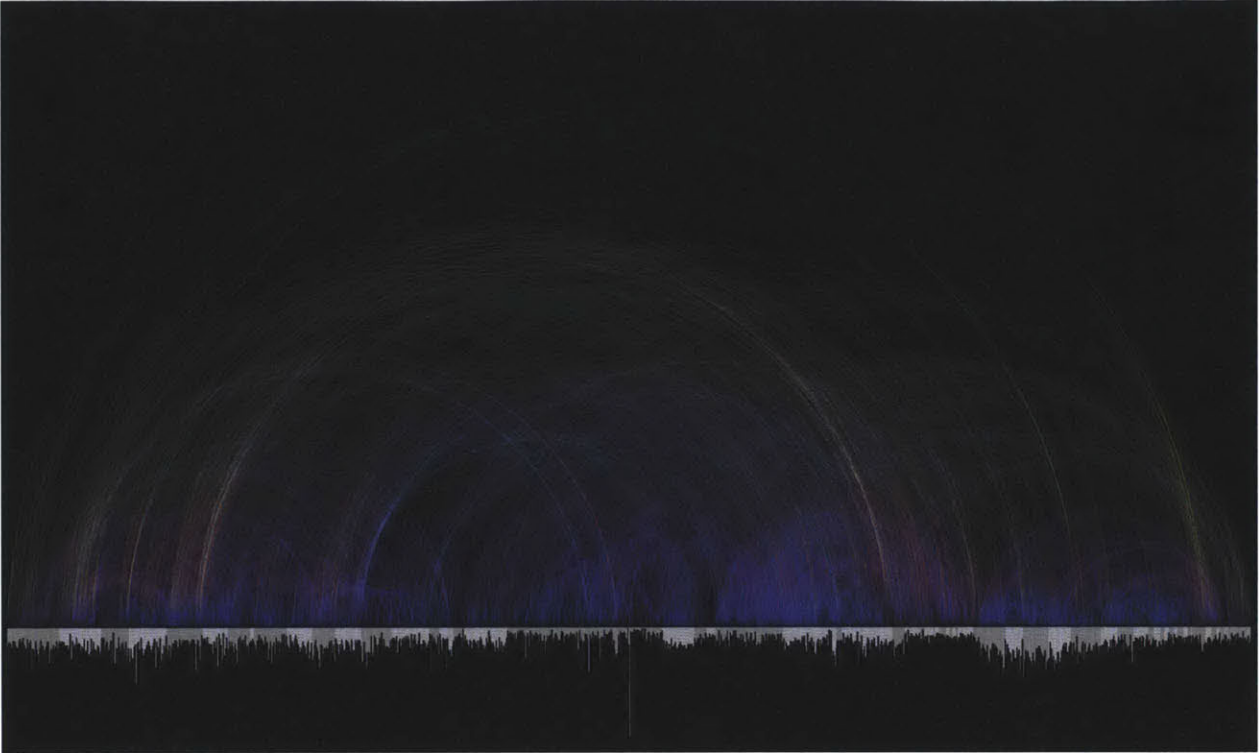




# RELATED WORK

The previous chapter identified two limitations of current display technologies that Display Blocks attempts to tackle: visualization and manipulation. This chapter contextualizes the research that my thesis work builds upon. It begins by reviewing screens that, by means of their shape, can visualize different types of content. It moves on to present work that explores shape as a cue to device manipulation and how it can be applied to digital visualization interfaces. Finally, I present a series of examples of multifaceted displays to lay the landscape around Display Blocks.





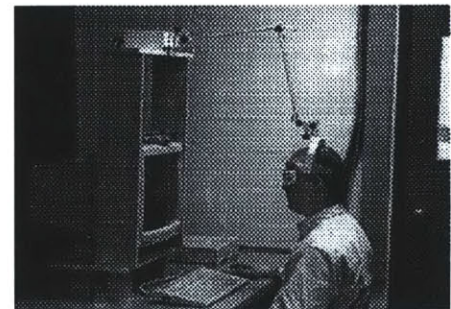
▲ Visualization of the Bible by Chris Harrison and Christoph Römhild. An example of flat visualization of multiple aspects of data. As described by the creators: “The bar graph that runs along the bottom represents all of the chapters in the Bible. Books alternate in color between white and light gray. The length of each bar denotes the number of verses in the chapter. Each of the 63,779 cross references found in the Bible is depicted by a single arc - the color corresponds to the distance between the two chapters, creating a rainbow-like effect.”

### 1. VISUALIZATION: TYPES OF DATA, TYPES OF DISPLAYS

The exponential growth in complexity and volume of data generates a need for continuous improvement in data visualization techniques. Current datasets have an increasingly large number of dimensions, making it hard to represent them on flat surfaces. Studies show that offering multiple perspectives on complex data can help us to both navigate and understand it better [18]. However, when we visualize multiple perspectives on a flat screen, we are not offered any cues about how the various perspectives relate to one another. Multifaceted displays, such as Display Blocks, have the potential of placing multiple data perspectives in a

single object. This way, the shape of the device can inform the viewer about the relationship between each of the faces. For example, if we place two screens at ninety degrees, we can infer that the information displayed in both screens has an orthogonal relationship. This relationship could either be literal - orthogonal perspectives on the same object, like top view and front view - or metaphorical - liberal versus conservative.

Color, shape and size can be used to represent multiple dimensions in screen-based data visualizations. Three-dimensional (3D) computer graphics are another widely used way to add dimensionality to data. Together with interactive tools, 3D graphics can help accurately represent volumetric data. Despite the realism that these visualizations can achieve, they are still delivered to us on a two-dimensional plane - the screen. There have been, however, some attempts to make screens better suited for 3D visualization. The term fish tank virtual reality was introduced by in 1993 Ware, Arthur and Booth [45] to describe a technique that paired perspective projection with head tracking in order to achieve the illusion of three-dimensionality in a flat display. In this method, when the user moves her head to the left, the image on the screen updates to reveal content to the right (which was previously hidden). Initial work relied upon a mechanical contraption being attached to the viewer's head, which could track location of the head and enable a sense of three-dimensionality. Subsequent work - such as the research by Ware and Lowther [46] - used cameras and markers to track a viewer's head, making such approaches less intrusive.



▲ First head tracking mechanism applied to *fish tank virtual reality* created by Ware, Arthur and Booth





▲ 360-degree volumetric display prototype, by SONY Corporation.



▲ One of the many scenarios envisioned by Balkrishnan, Fitzmaurice and Kutenbach in their paper. These types of displays do not enable direct manipulation and instead require alternative means to interact.

There are also four kinds of three-dimensional displays which explore how to represent volumetric digital data in a more realistic way: stereoscopic, autostereoscopic, holographic and volumetric displays. Stereoscopic displays rely on the stereopsis principles defined by Sir Charles Wheatstone - that is, they send a different image to each of the viewer's eyes, generating the illusion of depth. Such systems tend to require viewers to wear special goggles - either polarized or synchronized. Autostereoscopic systems can achieve similar results by tracking the user's eyes - or by knowing where they are - and use optical elements to direct different images to each eye. This being the case, autostereoscopic systems do not require spectacles. Building on the work by Gabor [9], holographic displays capitalize on properties of light reflection in order to visualize volumetric data. Volumetric displays are another approach to achieve similar results, relying on persistence of vision to generate three-dimensional visualizations while moving a rapidly changing LED display [10].

All of these technologies can be controlled through decoupled interaction - either by traditional inputs or by gestural interfaces. Balakrishnan, Fitzmaurice and Kurtenbach explored different means of interaction with such devices [4]; more recently, work by Grossman et al. experimented with multi-touch and pointer interfaces on top of volumetric displays [13, 14]. Work by Plesniak [29] goes beyond these input mechanisms to explore the creation of physical tools that give users the illusion of manipulating three-dimensional data as if it were real. In Plesniak's work,



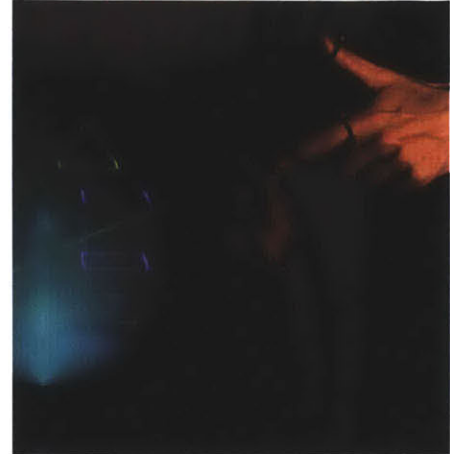


the user can sculpt a holographic form by means of a force feedback tool. None of these technologies, however, can be handled or operated directly, nor are they meant to represent data that is anything but volumetric. I seek to explore the impact of holding a multifaceted display in one's hands, which can visualize volumetric data, among many other types.

Display Blocks is an attempt to visualize data in a different way - capitalizing on the visual cues of a cube. The design of Display Blocks, with screens at ninety degrees from one another conforming a cube, can be leveraged to help users understand the relationship between the different visualizations on each of the faces.

## 2. INTERACTION: THE SCREEN AS AN OBJECT

As mentioned earlier, a knife, through its design, can reveal its purpose. Object characteristics which invite particular uses are known as affordances. If integrated properly into a digital device, affordances can encourage the manipulation and understanding of the information displayed - just as the design of a knife helps us understand how to hold it. The concept of affordance was first introduced by Gibson [11] to the field of psychology and was later applied to human-machine interaction by Norman [27]. A screen, as an object, has certain affordances; a screen is a frame to content, and, as already discussed, it builds upon our understanding of windows. As a consequence of this perceptual parallelism, we tend to assume that the content



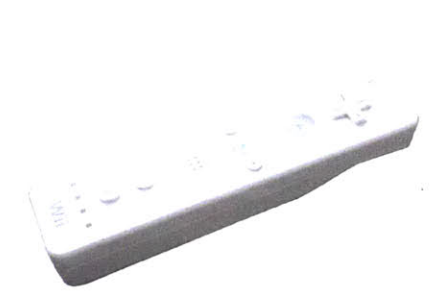
▲ Pointing gestures for interacting with volumetric displays as implemented by Grossman, Widgor and Balkrishnan.



▲ BumpTop is an application that allows users to interact with their desktops as if the icons were physical.



▲ One example of projecting oneself into the virtual world - or presence - is the exaggerated movement of a gaming controller in an attempt to command stronger reaction from a video game.



▲ the WiiRemote can act as a handle for digital information.

of a screen is subject to the same physical laws that in the environment surrounding it. When, for instance, we explore a three-dimensional object in a display, we assume that the parts that are closer to the top of the screen are higher and that gravity pulls objects to the lower part of the display. This establishes a tacit cognitive contract with viewers. Applications such as BumpTop [1] or Crayon Physics Deluxe [19] capitalize on this convention, allowing users to interact with virtual space in ways that they would interact with physical space. First described by Slater et al. in 1993 and further developed in other publications since [40, 35], this cross-reality phenomenon is called presence - the projection of self into a virtual environment.

While presence describes the projection of physical expectations into the digital world, other research has explored how physical objects can be leveraged to manipulate digital content. Building atop the aforementioned idea of affordance, Fitzmaurice, Ishii and Buxton introduced the concept of graspable interfaces [8] - physical objects which interface with computers to promote more meaningful human-computer interactions. Further work by Ishii and Ullmer [17] and Maynes-Aminzade [23] investigated how users can leverage their acquired intuition about certain objects to better understand digital systems; they called such systems tangible interfaces. This research has permeated the market via devices such as the WiiRemote - a gaming remote that maps its motion to manipulation of objects inside of a video game. The rationale behind this body of research is to provide physical handles to digital content, strengthening

the connection between the screen and the physical objects that surround it.

Recent years have shown how these two concepts - presence and tangible interfaces - are converging in the same object. As display technology is embedded in devices alongside touch, acceleration and rotation sensors, we continue to project our physical expectations into the digital world. Now, however, the same device is able to be leveraged as a handle for manipulating and exploring digital content. Tablet applications like Labyrinth [16] or Super Monkey ball [36] capitalize on this phenomenon to create incredibly realistic physical correlations between digital content and the real world. I believe that the implications of this coupling between input and output have the potential to go beyond physics simulation-based games to engage users in novel, more intuitive ways to explore data. Specifically relevant to the work of this thesis are ways to engage multiple tangible displays to visualize data from different perspectives.

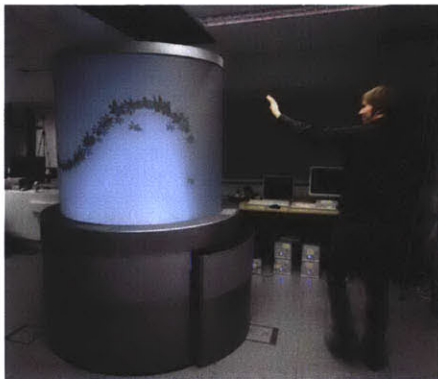
In the design process of Display Blocks, I want to build upon our perception of screens as objects and the implications a cubic arrangement for visualization and manipulation of data. I am interested in exploring the convergence between input and output in screen-based interfaces and how the arrangement of this displays can be perceived as an affordance to their content. Sheridan et al. [38] compiled a comprehensive study of the kinds of manipulation a cube supports. I seek to apply these ideas in creating interfaces to visualize and manipulate information.



▲ Tablet applications such as Labyrinth demonstrate the duality of screen as output and input to create physically realistic experiences.

### 3. NON-PLANAR DISPLAYS AND INTERACTION

There are a variety of projects that have explored the effects that large, static non-planar displays have on their audiences. For example, research by Beyer et al. demonstrates the affordances of large-scale cylindrical screens [6]. Their findings show that such form factors tend to foster a more explorative approach towards content consumption. Because of the cylindrical nature of these displays, users, instead of stopping in front of the screen to passively watch, are prone to walking around to see the hidden side of the display. Further research by Koppel et al. continued to explore this phenomena, analyzing how different arrangements of non-planar screens can influence an audience's behavior [20]. Work by Benko, Wilson and Balakrishnan further exposed the suitability of spherical displays for collaborative scenarios [5]. Additionally, work by Bolton et al. compared collaboration both in spherical and flat displays in a more in-depth set of experiments [7]. Across this body of work, there seems to be a common trend in the coupling of display shape and its function, as if the shape facilitates the function. This resonates with the concept of affordance and can be used to design more specific, task-oriented types of displays.

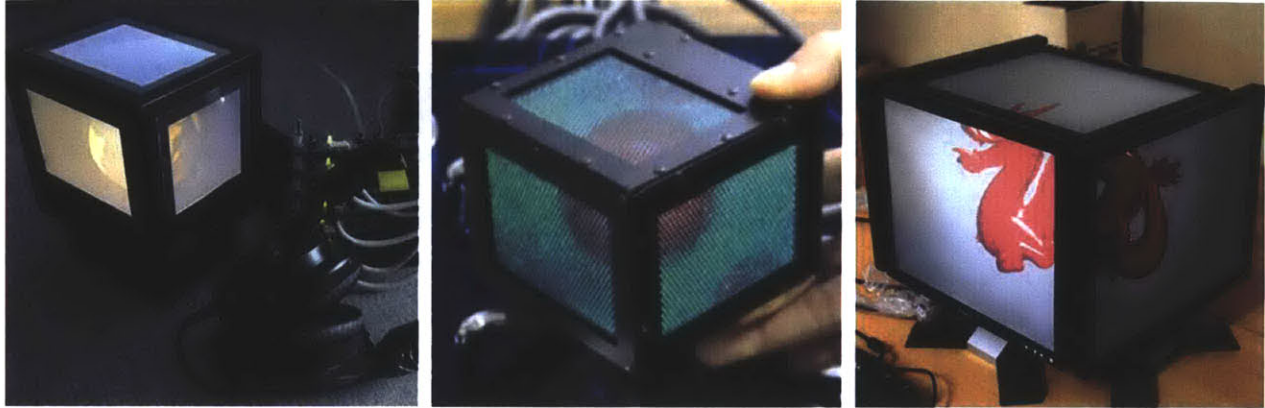


▲ Cylindrical display created by Beyer et al.



▲ Microsoft Sphere, a multi-touch spherical display developed by Benko, Wilson and Balakrishnan. In the picture users perform a photo arrangement task.

A particular instance of non-planar displays relevant to the work of this thesis is the cubic display. Several cubic displays have been developed for visualizing three-dimensional content. Work by Stravness et al. explored the idea of using a cube as a visualization tool for fish tank virtual reality in projects such as Cubee and its handheld



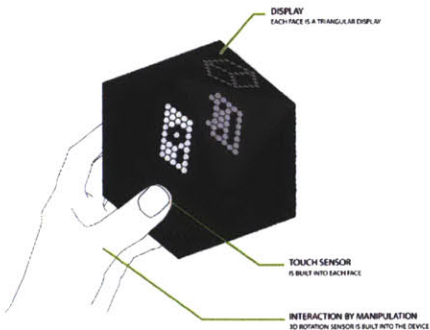
counterpart, pCubee [42, 43]. These two projects rely upon wearable hardware which tracks the user's eyes to simulate the appearance of a volume in the screen. Lopez-Gulliver et al. presented gCubik, a handheld autostereoscopic cubic display [22]. Due to its autostereoscopic nature, gCubik does not require any external tracking device to perform. However, also because of this, the screen brightness is reduced depending on the angle from which it is viewed. In a cubic display, each of the screens is at a different angle, so this can become uncomfortable - especially when manipulating the device. To broaden the possibilities in terms of form-factor of these kind of visualizations, Harish and Narayanan created a technology to support any polyhedral display arrangement by representing three-dimensional objects with fish tank virtual reality techniques [15]. Their system is able to use off-the-shelf liquid crystal display (LCD) panels, in conjunction with a head mounted camera system, which tracks the position of the screens in space with respect to the user. The system understands the screen arrangement and accurately generates graphics to create the illusion of volume. None of

▲ From left to right: pCubee (Stavness et al.), gCubik (Lopez-Gulliver et al.) and Polyhedral displays (Harish et al.).

these devices, even those that are handheld, are self-enclosed, and/or they require users to wear additional technology – like cameras or other tracking mechanisms. These two factors potentially hinder the manipulation features that these devices have to offer. Through the design of Display Blocks, I strive to create a completely self-enclosed technology that conserves the manipulative characteristics of the display as much as possible. Additionally, I believe that the cube shape is very well suited for many types of visualization, not exclusively for three-dimensional visualization (as explored in the above projects).



▲ Cubtile by Rivière et al. enables users to manipulate 3D models by means of a multi-touch cubic input device.



▲ D20 concept for a 20-faced interactive display, by Poupyrev, Newton-Dunn and Bau.

Focusing more specifically on interaction, several researchers have explored the potential for cubic and other types of multifaceted interfaces. CubTile, designed by de la Rivière et al., is a cubic interface that allows users to navigate 3D worlds [34]. In their research, they compare flat touchscreen technologies to CubTile for manipulation of 3D scenes. Although the screen in CubTile is not embedded in the interaction device, it is easy to imagine how these navigation techniques could be applied in some of the aforementioned cubic displays. In a similar fashion, Poupyrev et al. developed D20, a concept for a twenty-face interaction device [30]. Due to the impossibility of building a prototype with currently available technologies, they created a physical mockup that could imitate the intended interaction by simulating the output with a screen-based visualization. D20 better assesses types of content for multi-faceted devices that play off the possibilities of perceiving the relationship between different faces of the device.

Projects like Siftables and the subsequent commercial product, Sifteo Cubes, developed by Merrill and Kalanithi, further explore the physicality and manipulability of displays within a richer ecosystem of applications [24, 39]. The Siftables are a set of small, flat display units that can sense their neighbors. The premise of this work is that it is hard to arrange and sort information items using current displays and interaction tools, and that we are so much faster arranging physical objects with our hands. By breaking the screen into smaller pieces, not only do they enable a faster, more natural interaction with the information - but they also better convey the idea of an element or data unit. An element can be a letter, a number, a color, a picture or even a piece of music. Once understood individually, these elements can be recombined to achieve new results. For example, we can put two portraits together to make them look at one another or we can pour

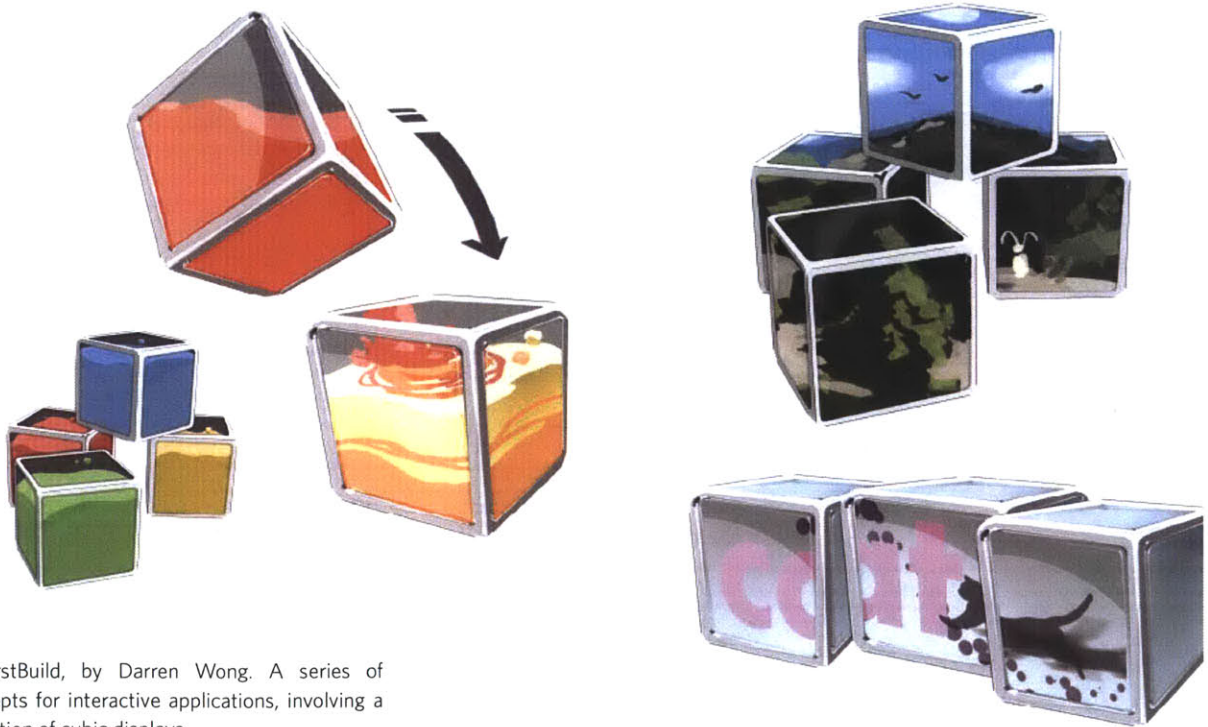


◀ Siftables by Merrill and Kalanithi. When we put to screens together their content knows and reacts.

▼ Sifteo Cubes are the commercial version of Siftables.



one color onto another to mix them. With a similar idea in mind, Designer Darren Wong conceptualized and illustrated a series of inspiring concepts meant for a collection of cubic displays, and he titled the project FirstBuild [47]. Applications such as volumetric puzzles are compelling examples of how Wong envisioned cubic displays could expand upon the possibilities of flat, display-based platforms like the Siftables. Another example of an application particularly well suited for a cubic form factor is LevelHead, by Julian Oliver, a virtual reality game played with cubes [28]. In LevelHead, each cube represents a room in a maze, and by tilting them one can make the main character walk from one side of the



▲ FirstBuild, by Darren Wong. A series of concepts for interactive applications, involving a collection of cubic displays.

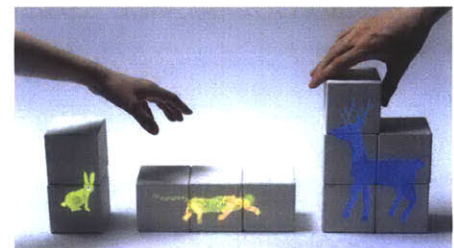


room to the other. When one connects different cubes, the character can walk into different rooms. This way, the user can explore the maze and try to find the way out. The cubes to play LevelHead are covered in tags that a camera system recognizes and augments with graphics onto a flat display, however, the content is easy to envision for a multifaceted display, where input and output are coupled. Finally, Tsumiki are a series of interactive games played with a collection of white cubes [31]. A projector shines content on top of the cubes, each of which is tracked with a camera. One of the more compelling facets of this project is how the system adapts content to the number of cubes on the table. Display Blocks seek to leverage the cubic form factor for compelling multi-perspective visualizations and applications in line with those of the above-mentioned projects.

A particularly practical case of an application integrated with form factor is A Cube to Learn. Developed by Terrenghi, Kranz and Hoellis, A Cube to Learn is an example of how to use a cubic display for a quiz-like interface [44]. The system is meant to be used as an educational tool and asks a question on one of the faces while offering different possible answers on the others. By rotating the cube in her hands, the user, can explore all the possibilities and select the one that she thinks is right by orienting that face upwards. A Cube to Learn is a coherent example of using the manipulative properties of a cubic display for interaction. It is my goal to create more of these kinds of applications for Display Blocks, in order to expand the possibilities of content in cubic displays.



▲ LevelHead by Julian Oliver is an augmented reality maze game played with cubes that represent different rooms.



▲ Tsumiki, a series of interactive applications projected on cubes. Upon detecting the arrangement of cubes, the system projects animals of matching shape.



▲ A Cube to Learn, being used by a child.



Given the amount of related work, it is apparent that there is an interest in expanding the possibilities for non-planar display technologies. All of these examples pursue different aspects of handheld, manipulable, multifaceted displays. However, there seems to be a disconnect between the development of novel display technologies and the design of suitable, corresponding applications. In the design of Display Blocks, I have striven to develop an integrated platform and set of initial applications. It is my hope that the applications will help exemplify the breadth of possibilities such devices can offer.







# FRAMEWORK, DESIGN AND APPLICATIONS

This chapter describes how ideas extracted from related research can help to address the previously introduced visualization and manipulation limitations of current displays. To that purpose, I compile a series of design guidelines to define a framework with which to address these limitations. Then, I work within this framework to propose a specific instance for such a display. Finally, I present a collection of applications which both inform the design and illustrate the possibilities of the Display Blocks platform.



## 1. FRAMEWORK

The objective of this thesis is to propose an design approach that tackles the two previously discussed limitations of current display technologies: visualization and interaction. After reviewing related work on technologies and applications for novel types of displays in the previous chapter, I have inferred a set of guidelines that inform the design of Display Blocks.

1. Enable the visualization of multiple perspectives on data. This can facilitate easier exploration and understanding of data, especially if the design of the display is used as a cue to the relationship between these perspectives.
2. Leverage the affordances of the physical design of the display to inform a user of its function.
3. Create applications that take full advantage of the chosen form factor. The design of devices and applications should be a two-way conversation.

These principles, despite being delineated to guide the design process of Display Blocks, may be of use to others designing similar systems. It is my intention to continue expanding this framework to accommodate other constraints as my work progresses.



## 2. DESIGN

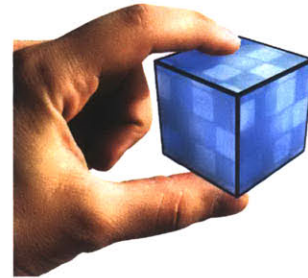
Building upon the three design guidelines above, I ideated Display Blocks: a set of handheld cubic displays that are able to visualize multiple perspectives on their content. A Display Block is composed of six screens arranged in a cubic manner. Each display on the cube is in sync with the other five, enabling coordinated visuals across the device.

This display configuration enables the representation of data from a variety of points of view - addressing the first design guideline. The form factor fits comfortably into an open hand and is able to detect basic gestures for interacting with content - covering the second design principle. Finally, I conceptualized a series of applications that demonstrate the potential of such device - fulfilling the third design criterion.

To better understand the nuances of the design of Display Blocks, I will describe the implications of the two most important features of the design: its shape and its size. These are two crucial aspects to understand the visualization possibilities of the displays and the affordances for interacting with it - closely related to the first two conceptual guidelines.

### ***The Shape: A Cube***

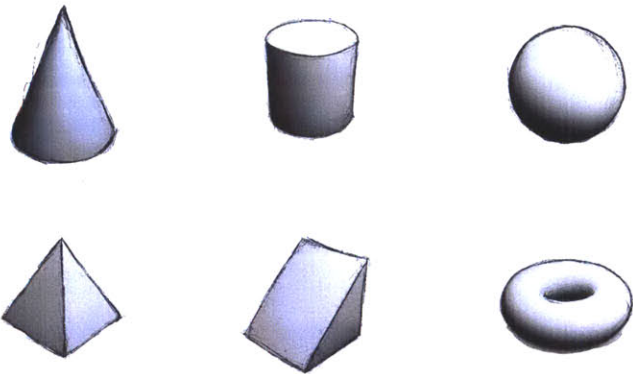
The cube is considered to be amongst the basic three-dimensional shapes alongside with other shapes such as the sphere, the cone, the wedge, the cylinder, the pyramid and the torus. When exploring the possibilities of new shapes for displays, I decided to start with a basic shape to better assess



▲ One of the initial design renderings for Display Blocks.



▼ Seven common 3D shapes. Top row from left to right: the cone, the cylinder and the sphere. Bottom row from left to right: the pyramid, the wedge and the torus. Bigger and to the left: the cube.



potential of a three-dimensional display before moving on to other, more complex, shapes. Amongst the basic three-dimensional shapes, the cube seems to embody the perfect balance between manipulation and control. A cubic shape is static and stackable - as opposed to the sphere, which rolls, or the cone, which only has one flat side. Cubes are also symmetric in all axes - unlike wedges or cylinders - making them modular and orientation-independent. Moreover, the fact that in the cube all of the faces are clearly delimited provides a reference when framing content.

The design of Display Blocks seeks to leverage the accumulated knowledge that users have of similar objects, and the shape of a cube is a very familiar one. One example of such an object is a construction brick; the same way we can build a wall from multiple bricks, Display Blocks can be





stacked to form larger structures as well. The shape of a cube also has a history of association with playfulness. Dice have accompanied the gaming experience for millennia and, more recent toys, like the Rubik's Cube are examples of how cubes are present in play.

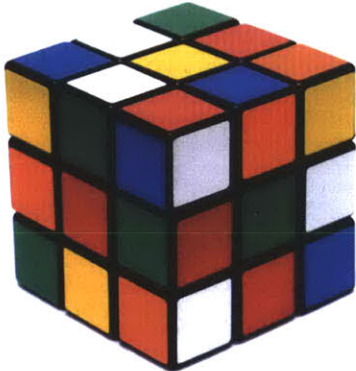
Building on users' familiarity with cubes in a more abstract sense, are orthographic perspectives - the basis of schematic and blueprint representation - which align with the faces of a cube. This fact can be leveraged as an affordance to understand the relation between content projected on the different faces of Display Blocks.

***The Size: Handheld***

To enhance manipulation, Display Blocks are designed to be a series of handheld devices. By holding a device in their hands, users are able to easily rotate it and reveal its different sides. Furthermore, creating a self-enclosed, autonomous device was crucial to offering unencumbered exploration of content. Requiring users to be close to a computer or physically attached to external hardware would interfere with the manipulative capabilities of the device. Keeping the weight to a minimum and selecting the right size were other challenges that I sought to tackle. Ideally, the design will support not only single device manipulation but also holding multiple devices at once. For this purpose, devices must be easy to manipulate using only one hand; this way, users can compare cubes side-by-side, adding even more richness to the navigation of data.



▲ Bricks are an instance of cube-like forms/shapes being used for building bigger structures.



▲ The Rubik's cube, a popular handheld puzzle.



▲ Bone-made Roman die from 1 AD. Dices are one of the oldest game devices created. The first die known is more than 5000 years old.

### 3. APPLICATIONS

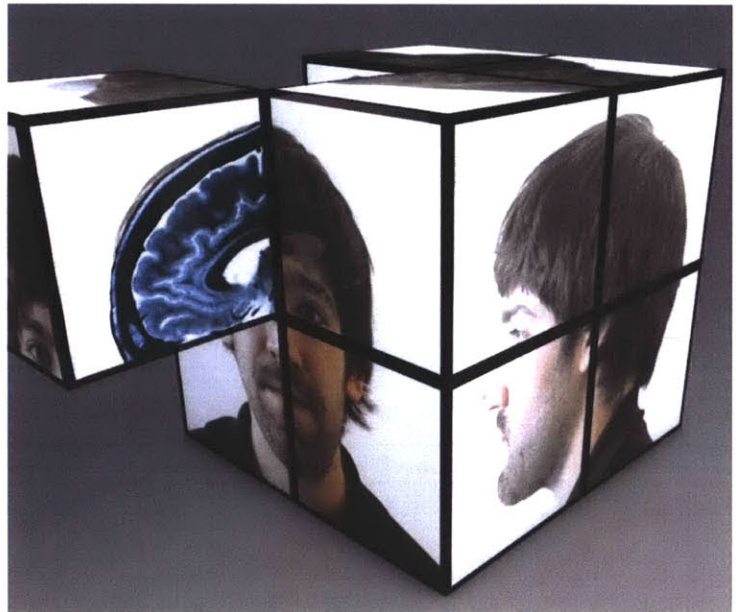
I have accompanied the design of Display Blocks with a series of applications that leverage the physical properties of this novel display. In doing so, I have focused on creating applications that are optimally experienced in this form factor. These applications explore different visualization possibilities with the intent of narrowing down which cases are most suitable for the technology. In the following paragraphs, I will describe these applications in detail.

#### *Orthographic Projections*

This application enables exploration of three-dimensional models by mapping orthographic perspectives onto the respective faces of the cube. While this is not an accurate three-dimensional representation in the way that



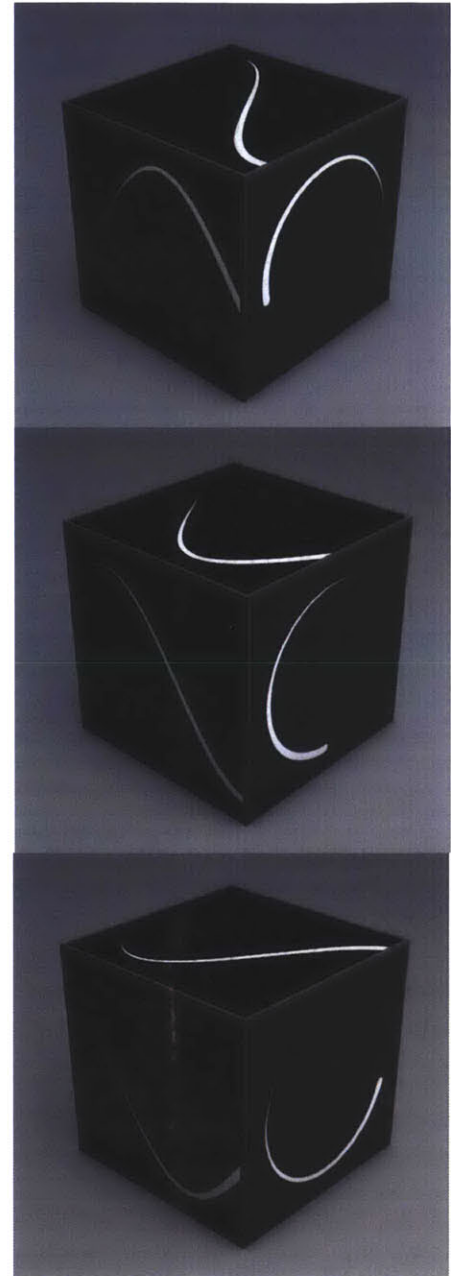
▲ Orthographic Projections application. To the right: application with a single cube To the left: application with multiple cubes. The models can be broken apart to reveal internal hidden content.



a hologram is, it enables the exploration of orthographic projections in their natural arrangement - that is, as if the objects represented were actually inside the cube and being projected out onto the faces. I am interested in how users relate to a model that they can hold in their hands as opposed to one displayed on a flat screen. Furthermore, by combining multiple instances of this display, we hope to allow users to explore objects that are best understood when they can be deconstructed. For example, if I were to compose a larger cube from eight of the displays in order to represent a beating heart, I could remove one of the cubes to look inside a ventricle.

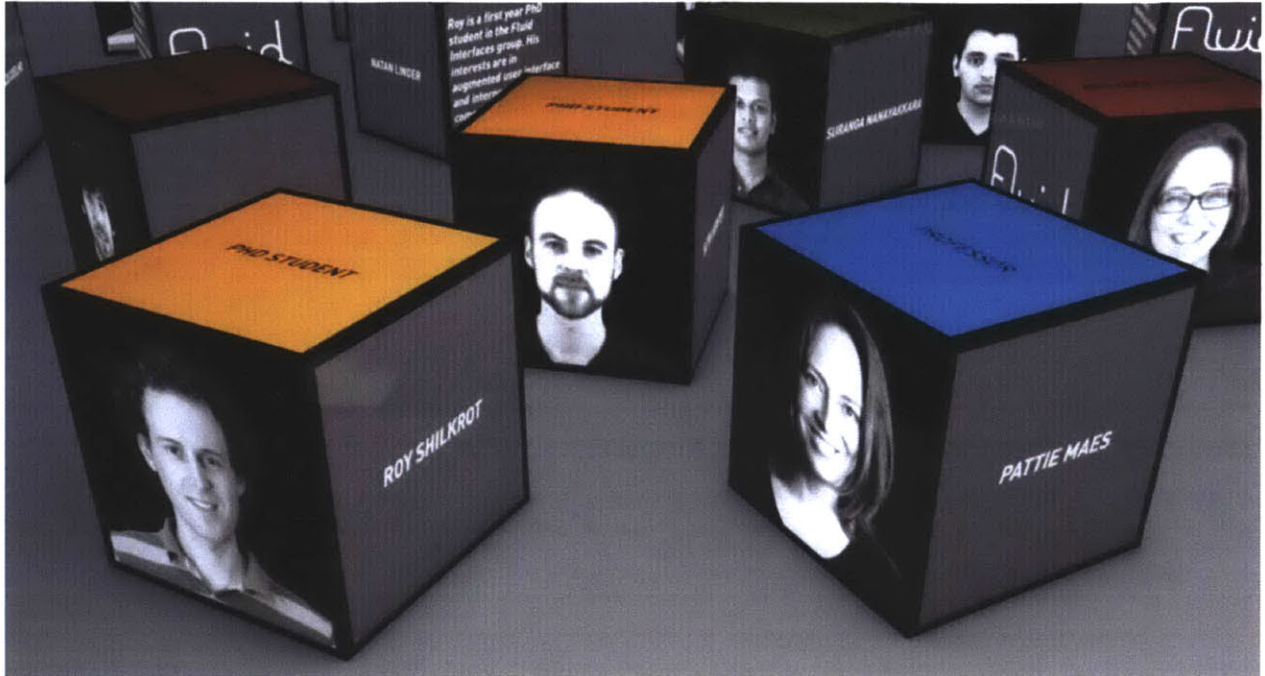
### ***Multi-Dimensional Visualization***

Display Blocks enable a new way of visualizing complex relationships, such as that between multiple dimensions like time and space. For example, the proposed device could show a video playing on one of its faces, while it shows the approaching frames on lateral displays. Similarly, while the front side of the cube could display an animation of a circle being drawn, the lateral displays could decompose this motion over time into a sinusoidal wave. This latter example could be useful for understanding complex physical phenomena such as the relation between speed and acceleration of a projectile.



▲ Multi-dimensional Visualization application. Display Blocks can visualize how circular motion in space can decompose into sinusoidal and cosinusoidal waves over time.





▲ Multi-Perspective Data Visualization. Each cube contains data about a person, each face of a cube provides one way to look at that person. The top face is color coded to ease the sorting of different cubes.

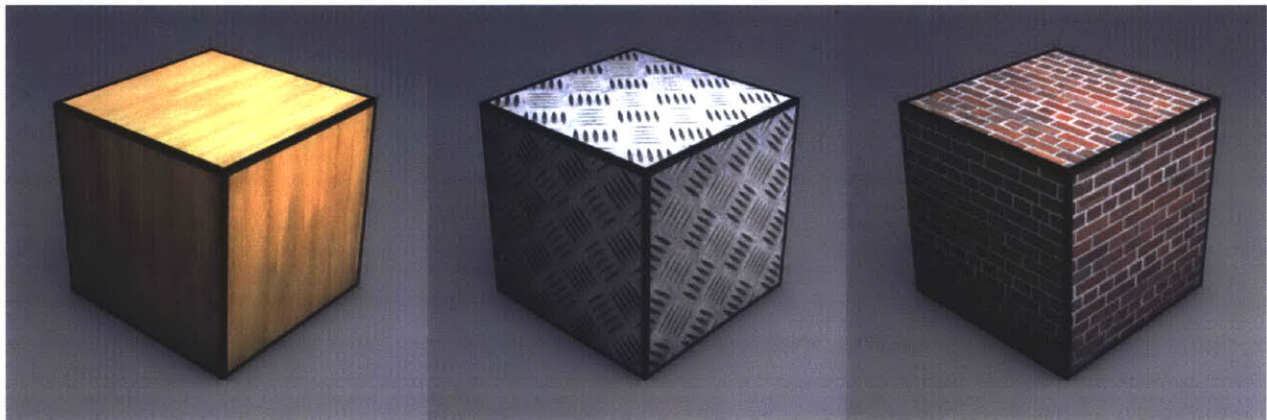
### ***Multi-Perspective Data Visualization***

A single piece of data can be represented in a variety of ways. For example, if the piece of data is a person, we might want to know her name, see a picture or find out her role in an organization. Similarly, if the piece of data is a word, we could translate that word into a variety of languages. This application explores how the multiple interpretations of a piece of data can be better understood when mapped to the different faces of a volumetric display. This capitalizes on the metaphorical relationship between faces and perspectives. The tangible aspect of the display enables playful and comparative explorations. Going back to the example with words, with multiple cubes, one could even construct entire sentences; by then rotating the cubes, she could translate an entire sentence into another language, word-by-word.



### ***Building Blocks***

This application explores how Display Blocks could be used as dynamic building blocks. Their cubic shape makes them easy to stack and group into different arrangements, making them suitable for customization purposes. Consequently, we can think of this volumetric display as a construction material - like a brick. If we build a wall with these novel bricks, we can change the wallpaper by sending a new image to be displayed on all of the screens. Projection mapping systems - such as Shader Lamps [32] - enable similar applications, but they require accurate calibration techniques; therefore, they are extremely sensitive to motion. By embedding the digital representation in the object, we can eliminate this problem. Pushed to the limit - by reducing and replicating these dynamically textured bricks - we could even realize customizable matter.



▲ The building Blocks application allows users to construct structures that they can then texturize. In the image: the same cube with different textures applied.



### ***Multi-Faceted Storytelling***

Based upon the intuitive alignment between multiple perspectives and different sides of a cubic display, this application proposes a new way to visualize and explore a story. The unique perspective of each character in a narrative is projected onto a side of the cube, in the form of a video or animation. This way, the viewer will be able to explore the story by manipulating and rotating the display. The cubic arrangement is particularly interesting because it enables users to focus on either just one face, or two or three faces simultaneously; yet, opposing faces of the cube cannot be watched at the same time, thus affording for a narrative use of the physical design.



► Display Blocks can be used as an alternative storytelling tool. A movie like Crash is one example of how a story with intersecting narratives could potentially be explored in such a device.



The design of Display Blocks resulted from an effort to marry application, form factor and underlying technology in order to create a novel display that presents information in more intuitive ways. Moreover, the applications demonstrate the versatility of the technology, which can be leveraged for multiple purposes across many disciplines.







# THE PROTOTYPE

Constructing the prototype for Display Blocks has been a significant technological undertaking. I have designed both the system hardware and software from scratch, and ensured custom assembly of the system. Because of this, the core concept is respected throughout each of these layers, as I have maintained control over all design variables and their integration. In this chapter, I describe the technology behind Display Blocks in detail. I begin to explain the rationale behind the creation of the prototype as well as each of the composing layers: hardware, software and assembly. Finally, I briefly describe the process of assembling Display Blocks.



## 1. PROTOTYPE RATIONALE

The key aspects of the Display Blocks prototype are hardware, software and design. The advantage of taking an integrated approach to building the system has been my ability to minimize the amount of black boxes in the device. A black box is a component that offers certain functionality, but that does not allow for modification; nor it is transparent as to how it functions. By maintaining control over all of the layers, the core concepts are respected and, at all times, the system can be further optimized or expanded to incorporate new functionalities or accommodate new interactions. This fits well with the main objective for the prototype, which was to construct a solid platform that enables future research to further explore the possibilities of such display technology.

## 2. HARDWARE

As mentioned in the previous chapter, the design of Display Blocks necessitated a small, self-enclosed device to enable manipulation at its fullest. Therefore, the main hardware challenge was to keep size to a minimum. Ideally, to achieve the perception of continuity between faces, the displays that cover each face of the cube should be the only visible part; the rest should be hidden. This implies that all of the supporting components for the screens to operate, including the battery, must fit inside the cubic display.

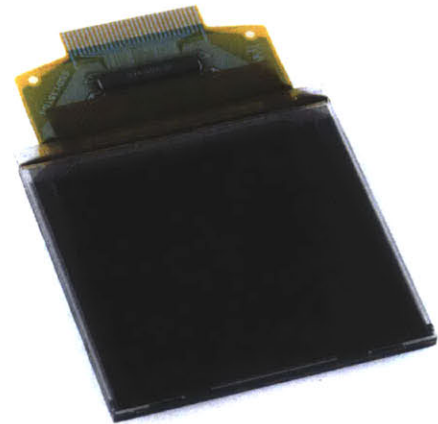
A secondary objective of the development of the hardware was to have an independent, fully-functional



screen for each face of the cube. This way, the same hardware could be used to create many types of arrangement beyond a cube. To that extent, I designed a standalone circuit board that includes all of the elements for each screen to be fully operational; this circuit board includes processor, memory, sensor, display, battery and supporting electronic components.

More specifically, each screen (or face) of a Display Block contains the following:

1. An OLED display – NewTech’s model NL128128C-EIF [25]. The size of these displays is 1.5 square inches and the screen area is 1.25 square inches. They have a resolution of a 128 x 128 pixels and they have a color definition of 262,000 colors.
2. One ARM 32-bit Cortex microcontroller – model STM32F103RET6 [40]. This type of microcontroller has a clock speed of 72MHz, 512kB of Flash memory and 64kB of SRAM memory. The speed of the microcontroller is crucial for enabling video functionality and the Flash memory is big enough to enable double-buffering, which eliminates flickering effects when generating graphics. Another important feature of this microcontroller is that it offers direct memory access functionality (DMA), which enables acceleration of some of the communication protocols and allows for computational processes to run in parallel.
3. One micro secure digital card (MicroSD Card) and reader. The SD Card is used for memory storage to allocate video and images.
4. One accelerometer to detect basic interactions such as shaking.
5. One lithium -ion battery and battery management circuit.



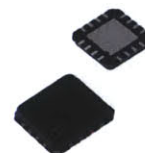
▲ OLED Display (NewTech’s NL128128C-EIF)



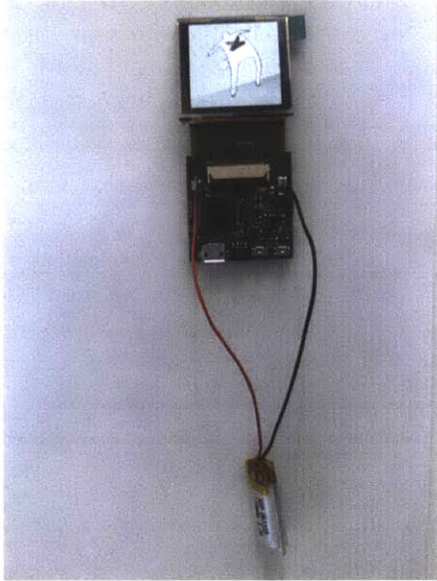
▲ ARM 32-bit microcontroller (STM32F106RET6)



▲ microSD Card

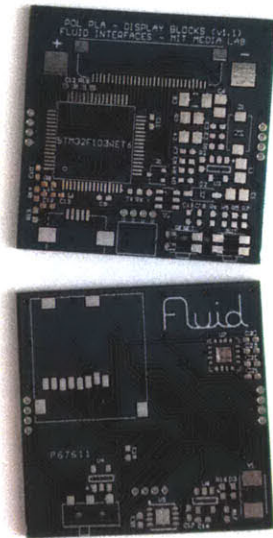


▲ Accelerometer (Analog Devices ADXL335)



▲ Final Assembly for one of the faces. Each face is completely independent in terms of functionality and it can be used in other arrangements besides the cubic form of Display Blocks.

▼ Final board behind every display. In the picture front layer on top, back layer on bottom.



I created a custom printed circuit board (PCB), accommodating all of the elements above plus the required components for them to work – such as capacitors and resistors. The board was routed in the Altium [2] software package and it measures 1.25 square inches, fitting perfectly behind the display. When six of these displays assemble into a cube, all of the electronics are concealed, achieving complete self-enclosure. However, to allow space for the batteries to fit inside the cube, the faces required some additional separation, resulting in a frame of roughly one third of an inch. In the future, this frame could be eliminated by designing a customized battery to fit inside the device. There is, however, already an unavoidable frame in the display, due to NewTech’s OLED having a margin around the active area of the screen. This frame contains the traces that enable individual pixel addressing and has a total width of a eighth of an inch.

For this first generation of Display Blocks, I simplified some of the functionalities so as to prioritize the robustness of the platform. To that end, I decided not to include wireless communication and to power each face from an individual battery. While this makes the prototype easier to work with during the test phase, it also makes it harder to reprogram and recharge the cubes once they are assembled. Upcoming versions will offer a solution to ease charging and reprogramming after the devices have been put together.

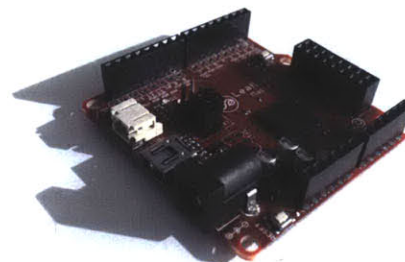
For more detail regarding the hardware for the prototype of Display Blocks please refer to appendix 1.

### 3. SOFTWARE

The microcontroller used for this project (the ARM Cortex STM32F103RET6) is the same used in the commercially available Maple board [21] and is therefore programmable through the Maple Integrated Device Electronics (IDE). The Maple IDE is open source software and provides basic microcontroller functionality upon which the Display Blocks code has been developed. Amongst the functionalities provided by the Maple IDE are: task and clock managing, basic communication protocols, pin addressing and event handling.

Each Display Block requires a very specific data flow. For each face, the system must be capable of accessing memory to retrieve images or videos and to be able to display graphics on the OLED screen. On a cube level, each face must be able to synchronize with the rest in order to coordinate graphics. To that purpose, my software to support Display Blocks encompasses three main functionalities:

1. Graphics capability: implementation and optimization of the protocol to address the 8-bit interface of the OLED display.
2. Memory management: interfacing with the SD card through a serial peripheral interface (SPI) optimized with DMA to speed up communication enough for video capability.
3. Synchronization with other faces: custom protocol implementation for synchronizing graphics throughout all faces of a cube.



▲ The Maple is a development platform for electronic projects it is open source and open hardware.



The software that I have written for Display Blocks has been fully developed to operate as a library. This means that it offers high-level functionality to developers, providing functions like *displayImage*, which coordinates between memory and screen to load an image. More generally, the library can support any type of basic drawing functionality, image display and video playback. This feature is complementary to the creation of independently functional faces in the hardware section. I took this approach because I wanted to enable others not only to create any configuration of displays, but also to be able to functionally program them without having to completely understand the code.

Using this library, I implemented three of the proposed applications for the final version of the prototype: Orthographic Projections, Multi-Dimensional Visualization and Building Blocks.

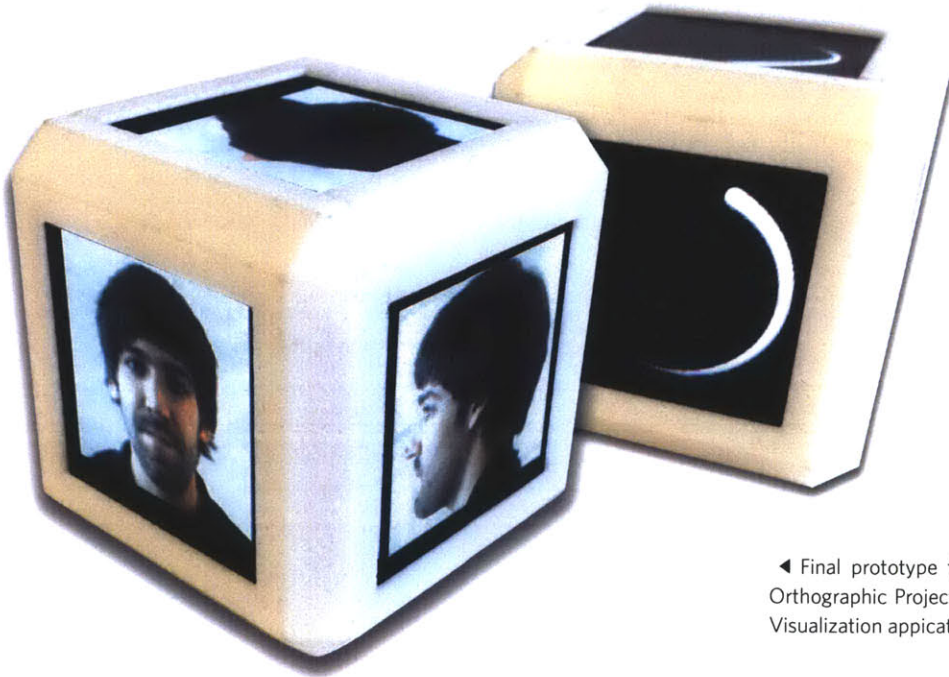
A collateral contribution of Display Blocks has been my work in optimizing the SD card access library in the Maple IDE. The necessity to have fast access to the SD card over SPI protocol to support video resulted in optimizations of the aforementioned library - specifically, by implementing SPI communication in conjunction with DMA. This enabled parallel processing and contributed to a 2,000% increase in read and write speed to and from SD cards. I have freely released the code that I generated for that optimization (via GitHub [12]), and it has since been officially adopted by the Maple community.



#### 4. ASSEMBLY

I designed a case for the final ensemble with the help of Amit Zoran. The case was designed using Rhino, a three-dimensional design software package [33]. Early prototypes were 3D-printed using the MIT Media Lab facilities and the definitive revision has since been produced by Shapeways, an online 3D-printing service [37].

The design of this enclosure is intentionally as minimal as possible to emphasize the displays as the focus of Display Blocks. It covers the rim of each display, keeping them bound into a cube shape but allowing one to fully view each display. To enhance manipulation, the case was designed with a flat bevel that makes it comfortable to hold and roll through the fingers of an open hand.



◀ Final prototype for Display Blocks, with the Orthographic Projections and Multi-Dimensional Visualization applications loaded.







# FEEDBACK

To evaluate the prototype of Display Blocks, I opted to conduct a series of interviews with experts across the fields of computer science, interaction design, data visualization and education. The goal behind these interviews was to compile early feedback from a variety of points of view and to inform further directions for the Display Blocks platform. Of particular interest were possible technological improvements, fields in which this kind of technology could be used, and specific applications that are well-suited for Display Blocks.





▲ Pattie Maes

The participants were selected to represent a wide variety of points of view. In the following paragraphs, I briefly introduce the interviewees, focusing especially on their research interests and how they relate to Display Blocks.

Pattie Maes is a professor at the MIT Media Lab, where she runs the Fluid Interfaces group. Her areas of expertise are human-computer interaction, intelligent interfaces and ubiquitous computing. Her extensive career in these three fields could offer keen points of analysis of the Display Blocks platform.



▲ V. Michael Bove Jr.

Michael Bove is the head of the Object-Based Media group at the MIT Media Lab. His expertise is in technologies for multimedia and screen-based experiences, as well as computer graphics and holography. Due to his end-to-end knowledge of interactive systems, he can provide insight on more technical aspects of the project, as well as to how various technologies could be integrated to support new interactions.



▲ Sepandar Kamvar

Sepandar Kamvar is an associate professor at the MIT Media Lab, where he directs the Social Computing group. His research focuses on social computing and information management. Due to his expertise in data visualization, I was interested in his assessment of the visualization potential for Display Blocks. Moreover, his previous experience in industry – as founder of Kaltix and head of personalization at Google – could be very valuable for considering Display Blocks as a product.

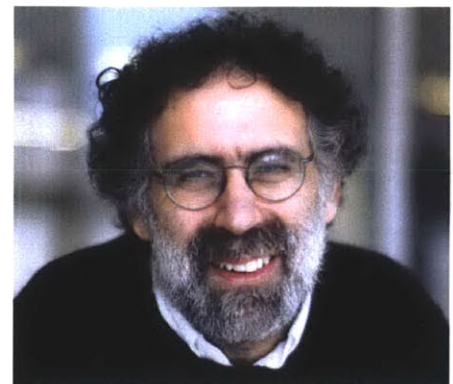
Neri Oxman is an assistant professor at the MIT Media Lab, and the director of the Mediated Matter group. Her background in design, art and material science contributes a unique point of view to Display Blocks, as she has deeply reflected on shape and materiality throughout her work.

Mitchel Resnick is a professor at the MIT Media Lab, where he also acts as the head of the academic program. He is in charge of the Lifelong Kindergarden group, where he and his students develop educational technologies that foster creative exploration and learning experiences. His comprehensive knowledge of the learning process was my main reason for interviewing him, as I wanted to gather his opinion on how Display Blocks could be leveraged as an educational tool.

Fernanda Viégas is a computational designer at Google, where she co-leads the Big Picture data visualization group. Because of her extended expertise in data visualization techniques, She offers a valuable perspective regarding the visualization perspectives for a system like Display Blocks.



▲ Neri Oxman



▲ Mitchel Resnick



▲ Fernanda Viégas



Each interview ran for approximately 30 minutes. I began by explaining the concept for Display Blocks, after which I presented the different applications and introduced participants to the working prototype. Finally, I proceeded with the following questions:

1. Of all of the applications suggested for Display Blocks, which do you find most compelling?
2. Can you think of other applications that might be well-suited for this technology?
3. What is, in your opinion, the potential of Display Blocks?
4. What do you think are the main limitations of this technology?
5. What other features would you like to see in future versions of Display Blocks?

I recorded the audio from each interview, afterwards analyzing and synthesizing the feedback so as to inform the further development of Display Blocks. Below, I present the aggregated responses to each of the questions, identifying any trends or points of consensus that emerged from the interviews.

***1. Of all the applications suggested for Display Blocks, which do you find most compelling?***

The answers to this question varied broadly, as there was interest in all of the proposed applications. Maes and Oxman agreed upon the power of tangible volumetric data visualizations, especially with multiple cubic displays,



and they both pointed to the Orthographic Projection application as their favorite application. Oxman went on to specifically suggest the use of this type of technology for exploring medical scan data. Bove found the simplicity of the Building Blocks application to be especially appealing, and thought it was worth further exploring the Multi-Perspective Data Visualization application. Resnick, coming from an educational perspective, found the Multi-Dimension Visualization especially interesting; he saw potential for explaining complex phenomena through a variety of linked examples. Viégas and Oxman also gravitated toward the Multi-Faceted Storytelling application. Oxman pointed out how current displays have shaped the way we experience narratives and thought it was interesting to explore how new types of displays might help further diversify storytelling methodology.

Some participants pointed out, correctly, that the current applications are still in an early stage of development. Maes, for example, mentioned that she would like to see the Orthographic Projection application merging with the Building Bricks. That way, she said, a user could build a house out of a few blocks and then open it up to reveal people and interiors inside. This would not only be interesting to explore in terms of play, but also for architectural planning – for example, to model the flow of people through a building. Bove, who is acquainted with current visualization techniques in the medical field, also saw potential for Display Blocks to support – or even replace – current visualization tools in the medical field. However, he pointed out that I would

*“Dynamic applications capture my attention the most; they get me thinking.”*

MITCHEL RESNICK

*“It would be interesting to build a whole city with Display Blocks and be able to look inside the buildings.”*

PATTIE MAES



*“I think of the data visualization app as a volumetric table; there are so many more interesting things that you can do to visualize information with Display Blocks.”*

FERNANDA VIÉGAS

*“None of the applications is the killer app, yet.”*

SEPANDAR KAMVAR

first need to understand doctors’ needs and the current applications used before I could claim the use of Display Blocks for medical imaging. Viégas had a very interesting reflection regarding data visualization, relevant to the case of the Multi-Perspective Data Visualization application. She said that as the application stands now, each Display Block is essentially a volumetric row of a table; each cell is mapped to one of the faces. She suggested that there are more interesting information arrangements that would make the visualization on such devices increasingly useful. For example, she recommended using more intuitive mappings like color, brightness or textured patterns, which she called *pre-attentive mappings* – meaning that they do not require deep cognitive engagement to be understood. She also suggested that the top face should always contain an aggregated view of the content that could then be decomposed in detail onto the rest of the faces.

In a more general sense, Kamvar pointed out that none of the current applications, despite being intriguing, constituted a “killer app”. Pursuing a killer app, in his opinion, is key to making a case for this type of technology.

## ***2. Can you think of other applications that might be well-suited for this technology?***

Taking into consideration that the conceptualization of the five initial Display Blocks applications happened over several months, this question was a hard one to answer on the spot. Some participants seemed comfortable brainstorming



about possible applications, while others focused more on strategies for devising new uses for the technology.

In one category, Oxman and Maes suggested exploring the multi-faceted nature of the cube to represent information traditionally found in that same arrangement. Oxman suggested that sensor data can offer different perspectives on a space. Using the different faces of the cube to visualize different qualities of a space would turn the cube, in her opinion, in to the ultimate ambient orb [3]. Maes, on the other hand, suggested using the device for social applications - i.e. visualizing information about friends and loved ones, or for mapping information accessible via the internet. She seemed very interested in mapping human relationships onto a display that can visualize such complexity better. Bove, meanwhile, suggested exploring communication between cubes in different locations. He suggested creating an input cube, with a camera embedded in each face, that would stream video to a remote Display Block. He showed interest in exploring this mapping with other types of sensors as well.

In another category, Kamvar, for example, pushed me to define a personal need and pursue an application that would solve it in the best way. He encouraged me to focus on applications requiring only a single Display Block, but to also keep scalability to multiple devices in mind. Resnick encouraged me to find visualizations where the cubic arrangement of the display informed users of either the use or the relationship between the content on different

*“The cube could be a multidimensional mirror of reality.”*

NERI OXMAN



*“This form factor is great for manipulation. You want to turn it around and continue to explore.”*

PATTIE MAES

faces, similar to the time-space decomposition for the Multi-Dimensional Visualization application. He quoted Marvin Minsky in reminding me that we only truly understand things when we have experienced them across a variety of cases and from multiple perspectives [25]. Resnick, Bove, Viégas and Kamvar all pointed out that incorporating more sensors into the prototype would yield new use cases. Both Bove and Resnick suggested that in doing so, it would be helpful to begin defining a grammar of interactions with Display Blocks.

### **3. What is, in your opinion, the potential of Display Blocks?**

All of the interviewees seemed to agree that the form factor of Display Blocks had implications that could support specific types of interaction. Kamvar, Oxman and Viégas agreed upon its suitability for play. Kamvar did so, after having been throwing the prototype from hand to hand throughout the entire interview. Oxman reflected on the die being one of the oldest methods of play and how the cubic shape of Display Blocks might evoke a similar connotation. Similarly, she offered a reflection about bricks as an ancient technology whose use in construction could be transferred to Display Blocks. Finally, Maes and Oxman mentioned how the multi-faceted nature of a cube affords for representing multiple points of view on such a display.

Discussing the physical properties of the cube, Viégas talked about how the shape of the cube supports both focused and scattered attention better than any other volume. “You can look at a cube,” she said, “in a way that





you can only see one face. As well, you can rotate the cube to offer up to three different faces at once. In other volumes, such as a triangular pyramid, you are always seeing, at least two faces." This is in contrast to a double-sided screen, in which one can only see a unique side at the time. The shape of the cube, she added, is specially suited for interaction with content. In a traditional graphical user interface (GUI), one usually needs to hover to get detailed information about an specific piece of content. The cube being volumetric is already magnifying information from the start, offering the potential of disambiguating data by looking at other faces.

In general, all of the participants agreed that Display Blocks offer great potential for manipulation. Bove and Resnick even specifically suggested to support richer interaction by sensing how the device is being manipulated.

#### **4. What do you think are the main limitations of this technology?**

There seemed to be unanimous agreement among interviewees that there were no limitations in terms of the form factor. Participants preferred talking about design features instead. As Kamvar pointed out, good designers work within limitations. He went on to encourage me to take full advantage of the features of the form factor, instead of focusing on its limitations.

Oxman and Kamvar did expose the rigidity of the form factor as a potential obstacle to competing with the portable screen-based devices such as smartphones or

*"Instead of the traditional mouse hover, your cubes already offer the augmented information."*

FERNANDA VIÉGAS

*"The interesting thing about the bricks is not where you put the together but where you break them apart, you need multiple instances of Display Blocks to achieve that."*

V. MICHAEL BOVE JR.

*"Finding the natural mappings to interact with the content might be hard, but it is very important."*

MITCHEL RESNICK



*“As a die, the iPhone is more limited than Display Blocks; as a phone Display Blocks are more limited.”*

SEPANDAR KAMVAR

*“You need a lot more input, to really exploit the physical properties of the cube.”*

V. MICHAEL BOVE JR.

tablets. They both subsequently expressed interest in a future version of Display Blocks that could fold, offering a transition in terms of both content and shape.

Focusing on the current prototype, Maes pointed out the thickness of the borders as potentially interfering with the experience. She thought that by having too much of a border, the continuity between displays breaks down. She pointed to the decomposition in time and space in the Multi-Dimensional Visualization application as a case where this happened. Finally, Bove and Resnick reflected on the limited sensing capability and how this reduces possibilities for interaction.

##### **5. What other features would you like to see in future versions of Display Blocks?**

Regarding this question, interviewees seemed to be unanimously in favor of focusing on the incorporation of sensors. Kamvar, for example, made a strong case for adding a microphone to enable voice recording or to detect when users blow on to the device. He, however, reiterated encouragement in experimenting with as many sensor capabilities as possible – as they might yield new uses for Display Blocks. Bove, Viégas, Resnick and Maes all suggested sensor capabilities that capitalize on the manipulative potential of the cubic form factor. To that extent, Bove suggested detecting orientation and enabling selection of content by means of converting each face into a different button, or even enabling touch and simple gestural recognition on top of each screen.



Viégas abstracted her answer from any specific technology, but pointed out the importance of having a way to select a specific piece of content. Resnick expanded on his previous suggestion of defining an interaction language, based on the addition of sensors which can track how the cubes are being manipulated. Bove also suggested enabling squeezing as an interaction. Although he acknowledges the complexity of achieving such a functionality, his idea seems well-suited for mappings such as compression or expansion - like a volumetric analog to the well-known multi-touch pinch gesture.

Viégas and Bove also showed interest in tracking Display Blocks in space. Bove suggested it would be a great addition to the Orthographic Projection application; the cubes could then show different parts of a three-dimensional scene, depending on their position in space. Viégas, on the other hand, expressed interest in tracking functionality to further explore the Multi-Perspective Data Visualization application. She imagined a scenario where the content of the cubes could change depending on their positions, allowing one to explore a gradient of content between two points in space. She also mentioned how, with this functionality, cubes could be used as multifaceted lenses to augment a flat visualization - for instance, a map.

Connectivity was another popular demand. Kamvar and Bove pointed out the advantages of using wireless connectivity to access remote data, either from sensors or from the internet. Bove and Maes also wanted to see

*“The more sensors the better. They will help you come up with new applications.”*

SEPANDAR KAMVAR

*“Let’s think about the communication between an ecosystem of Display Blocks; either if it is between two of them sitting side-by-side on a table or in two different rooms a thousand miles away.”*

V. MICHAEL BOVE JR.



connectivity between cubes, enabling similar interactions to the ones exemplified by Siftables [24]. Finally, Viégas proposed controlling content displayed on the cubes with a traditional GUI on a flat display.

I interpret the overall positive nature of interviewee responses as a sign that this research is headed in a promising direction. It was especially helpful to hear some interviewees explain nuances of their respective fields and how the initial applications could benefit from these insights. I look forward to start incorporating the feedback received in coming versions of Display Blocks.





# FUTURE WORK

As it can be observed in the interviews, the Display Blocks prototype shows promise for a variety of uses. However, there is still a lot to explore, especially regarding applications and interactive capabilities of the device. This first stage of Display Blocks has served as a proof of concept for the design and has also yielded a robust prototype that can be used as a foundation for exploring new functionality. I am excited by the prospect of developing this technology further in a variety of directions. In this chapter, I analyze the main possibilities for expanding beyond the current Display Blocks platform in terms of applications, interaction, design and technical improvements.



## 1. APPLICATIONS

One of the most promising future directions for the work of Display Blocks is to continue expanding the landscape of applications. The design of applications is a double-edged sword: it helps to showcase the advantages of the device, but simultaneously, it exposes technical limitations of the platform that could be improved upon. A couple of especially appealing fields for future applications are gaming and social media. Although it is not my intent to turn Display Blocks into a gaming platform nor a social media support, I do believe that broadening the spectrum of applications can strengthen the case for this novel screen form factor.

As I introduced in the design considerations and as was pointed out by some interviewees, the form factor of Display Blocks invites playful interactions. For example, capitalizing on the unique coupling of visualization and interaction, the platform can enable novel gaming experiences. Volumetric puzzles or games that have a three-dimensional component, such as LevelHead [28], served as interesting starting points for further exploration in this space.

Similarly, some interviewees pointed out the suitability of Display Blocks for social media experiences, due to the device's capability to visualize multiple perspectives on data. Social media emerged on the internet and subsequently expanded to mobile devices – all of which are flat displays.



Social media applications for Display Blocks could offer a completely different way to experience this type of content. As relationships tend to be multi-faceted in nature, the shape of Display Blocks may be especially well-suited for reflecting this.

## 2. INTERACTION

The current prototype of Display Blocks and the initial applications designed for it have already revealed a need for increased interactive capabilities. Potential areas for improvement (as it pertains to interaction) fall into three overarching categories: sensing, connectivity and spacial awareness.

### *Sensing*

The current capability for direct manipulation in the Display Blocks prototype is somewhat limited - accelerometer data is used to detect when the device is being shaken. Improving the processing of accelerometer data alone would support richer, more complex interactions. For example, users could move content from one face to another by rotating the cube in an specific direction. These kinds of functionalities would contribute to a more tightly coupled experience between content and form factor.

Another way to engage users in more direct manipulation of content would be to focus on interaction with each of the faces of the cube. Turning whole faces into pushbuttons or adding touch sensing on top of the current



infrastructure will enable the selection of content and the recognition of basic gestures to manipulate parts of the content. Coordinating these sensing capabilities across the different faces could enable even richer manipulation of content - i.e. manipulating multiple dimensions at the same time.

Alternative ideas involve a variety of sensors such as microphones, cameras, temperature or light sensors. As one example, by adding a microphone to a Display Block, sound could be recorded and analyzed. Each recording could then be decomposed into different frequencies, mapped and visualized on the different sides of the cube. In the case of cameras, input devices could be designed to work alongside Display Blocks. One instance of this could be an input cube with six cameras - one on each face - that could then be mapped to the analogous six faces of a Display Block. This application could be interesting for videoconferencing or remote collaboration scenarios. Finally, Display Blocks could become an ambient device by enabling the sensing of temperature, light levels or other types of environmental data. After gathering data, a Display Block could allow users to explore this data from multiple perspectives.

### **Connectivity**

Connecting Display Blocks to one another, to different devices such as cellphones, tablets or computers and, ultimately, to the internet would open up a variety of new interaction possibilities. Allowing cubes to communicate with adjacent cubes, for example, would allow data exchange



between them as well as it would enable each cube to react to its neighbors. Connecting Display Blocks to other devices would support the creation of hybrid systems that capitalize on the familiarity of traditional screen-based interaction, but that benefit from the unique visualization capabilities of Display Blocks. Finally, internet connectivity would enable a variety of improvements to the current prototype, ranging from data access to cloud services.

### ***Spatial Awareness***

By knowing their position in space, the cubes could act as volumetric windows into a digital reality. That is, a cube that knows its exact coordinates in space could display the portion of a digital world matching those same coordinates. This would be especially interesting with a series of cubes, allowing one to explore complex three-dimensional environments just by positioning the cubes in space. Investigating different tracking techniques - for example, magnetic-based position detection or signal triangulation - could enable these kind of interactions.

## **3. DESIGN**

The current form factor of Display Blocks does not allow for high resolution imaging. Consequently, I am interested in exploring other scales for Display Blocks. These new sizes would, of course, change the affordances of the device; bigger sizes would make Display Blocks seem more stationary. As display technology evolves, I would also like to experiment with alternatively shaped screens - such



as triangular or flexible displays - that would allow the composition of other volumetric shapes.

The design of cellphones and other computational devices strives to create thin and portable devices. Volumetric displays, such as Display Blocks, because of their nature, are not very well suited for the same purposes. Thus, I am also interested in exploring ways that these devices could fold for the sake of portability. Moreover, it would be interesting to explore how content could transition between the volumetric and the planar states in such a device. Perhaps unfolding would expose the dimensionality of the data, and folding would collapse all of these dimensions into a single aggregated view.

#### **4. TECHNICAL IMPROVEMENTS**

The biggest technical limitation of the current Display Blocks prototype is that it requires a cable to charge the battery and program each cube. This makes it cumbersome to connect multiple Display Blocks at the same time, consequently hindering the potential for scaling up the number of blocks simultaneously in use. Incorporating radio receivers on to the current prototype would allow for programming each cube remotely. Similarly, integrating induction charging into the prototype would allow for wireless charging stations, and would completely eliminate the need for cables.



As I move on to pursue further research on Display Blocks, I will rely on the solid conceptual core and reliable prototype developed throughout this thesis. I plan to expand the central idea of building displays better suited to their content and that afford intuitive manipulation. Following a concept-driven approach, I will allow the development of applications to drive the supporting technological enhancements.





# CONCLUSIONS

It is my belief that the design of display technologies can better accommodate both the large amounts and complexity of information, simultaneously facilitating more natural ways of interacting with that information. Display Blocks is my attempt at creating a novel type of display that addresses this. I focused on visualizing multiple perspectives on data so as to invite exploration of content. I received very positive feedback on the first prototype, confirming that an interface like Display Blocks can influence the way we manage and visualize information.



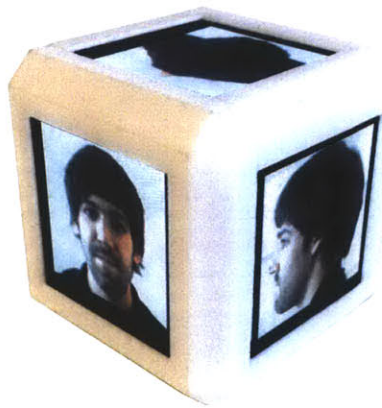
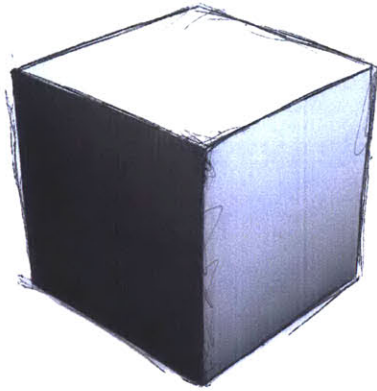
It is my belief that technology is evolving from multifunctional devices to an ecosystem of minimal, task oriented ones. In the context of display technologies, I see Display Blocks as part of a palette of visualization devices. When one works with clay, one can use a variety of tools depending on what one wants to achieve; similarly, when one deals with the representation of data, one should have access to a broad set of display technologies. It is my hope that Display Blocks may inspire others to explore form as a design variable in the creation of novel displays. Furthermore, I look forward to seeing similar approaches applied to an ecosystem of technologies that better appeal to our shared human nature.

On a personal level, the creation of Display Blocks has been an amazing learning experience. Not only it has expanded the foundations of my knowledge in a variety of disciplines, but it has also enabled me to see the connections amongst them. By creating a system from scratch, in which I understand every single layer, I have witnessed the dialogues amongst these layers - which have consequently informed my decisions throughout. Moreover, including a variety of points of view in the evaluation of my work has offered helpful feedback to expand the project in multiple directions. Such multidisciplinary approach broadly expands the variety of points of view on one's creative work.

I see the conclusion of this thesis as a good point to continue exploring the possibilities for more intuitive types of displays.







◀ The evolution of Display Blocks. From concept to design, and, finally, implementation



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# APPENDIX 1: HARDWARE

This chapter includes all of the information needed to replicate the hardware in the current prototype of Display Blocks. I include a list of materials, schematics (with a detailed description about each part of the circuit), a large spread of the circuit board layout and an overview of the assembly process.

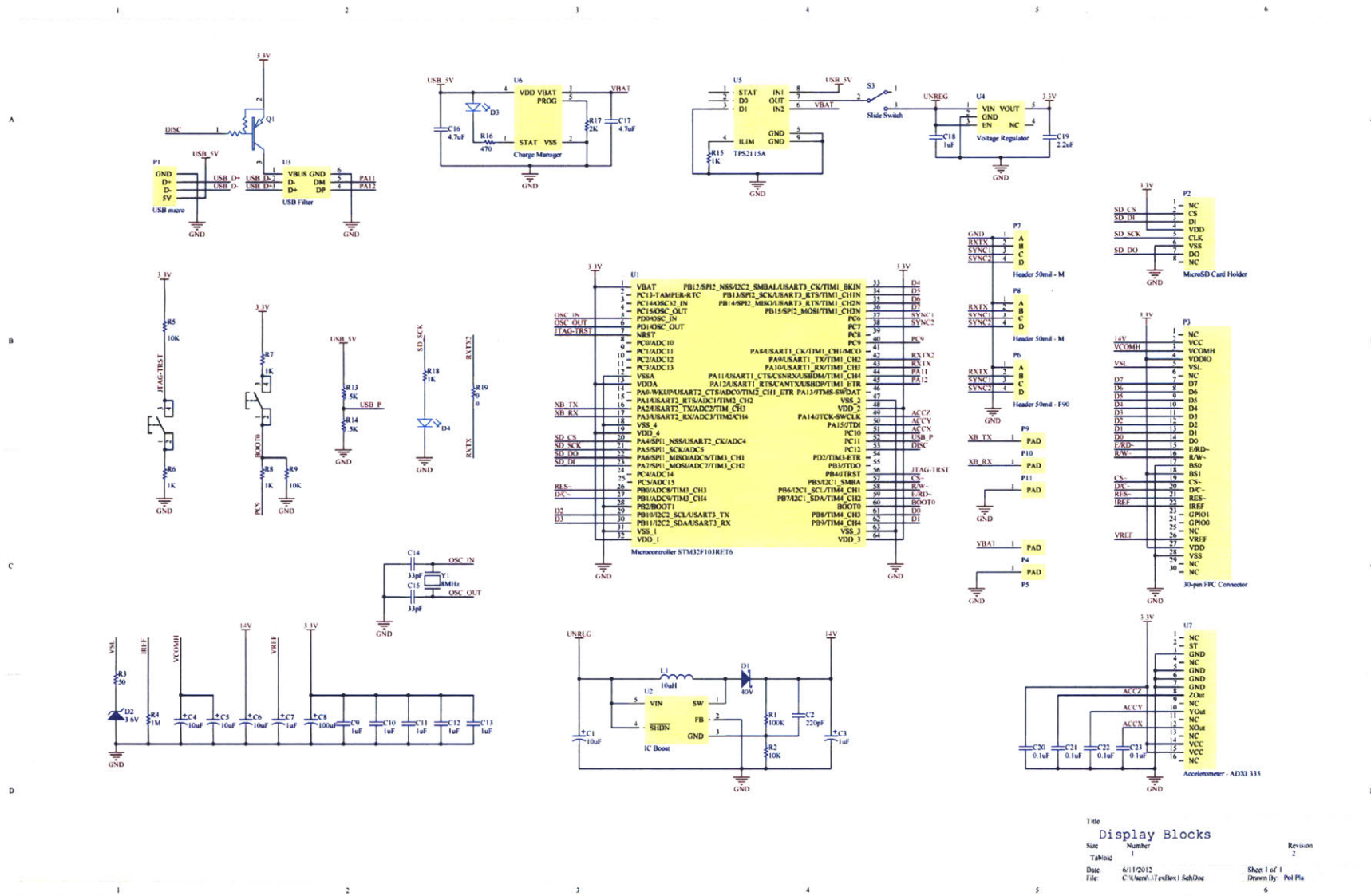


## 1. LIST OF MATERIALS (for one face)

Amount	Component
1	32-bit ARM-based Microcontroller (STM32F103RET6)
1	128x128 pixel OLED Display NL128128C-EIF
1	Connector FPC 30-pin
1	Connector microSD Holder
1	microSD Card 2GB
1	Li-Ion Battery
1	Charge Manager Li-Ion
1	Accelerometer ADXL335
1	Crystal 8MHz
1	Power Regulator (LDO) 3.3V
1	Voltage Input Selector
1	Connector USB micro
1	USB Filter ESD Protection
1	IC Voltage Booster
1	Switch Slide
2	Switch Tact
1	Transistor PNP (10 kOhms)
2	Diode LED Green
1	Diode Schottky 40V
1	Diode Zener 3.6V
1	Inductor Multilayer 10uH
1	Resistor 2KOhm
1	Resistor 470Ohm
2	Resistor 1.5KOhm
5	Resistor 1KOhm
3	Resistor 10KOhm
1	Resistor 1MOhm
1	Resistor 50Ohm
1	Resistor 100KOhm
4	Capacitor Ceramic 0.1uF (10V)
2	Capacitor Ceramic 4.7uF (10V)
1	Capacitor Ceramic 2.2uF (10V)
6	Capacitor Ceramic 1uF (16V)
1	Capacitor Ceramic 220pF (50V)
2	Capacitor Ceramic 33pF (50V)
1	Capacitor Tantalum 100uF (10V)
4	Capacitor Tantalum 10uF (16V)
2	Capacitor Tantalum 1uF (16V)



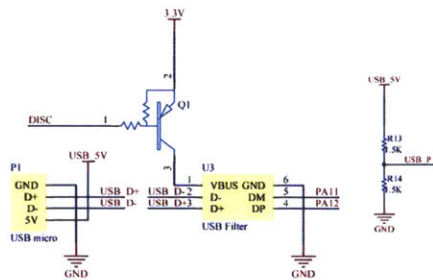
## 2. SCHEMATICS



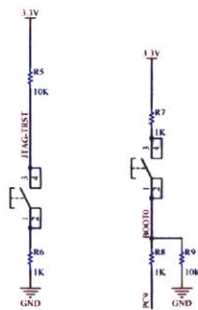
### Microcontroller Circuit

Each face of Display Blocks includes a 32 bit ARM-based microcontroller (STM32F103RET6). According to the data sheet for this microcontroller, it requires an external clock at 8MHz, regulated power at 3.3V, an interface to USB, and two buttons that are used to reset and program the microcontroller. Diagram A shows the microcontroller schematics. Diagram B shows the circuit for the external clock. Diagram C shows the voltage regulator circuit. In Diagram D, the circuit to support the USB interface is shown. Finally, Diagram E shows the two circuits for the buttons.

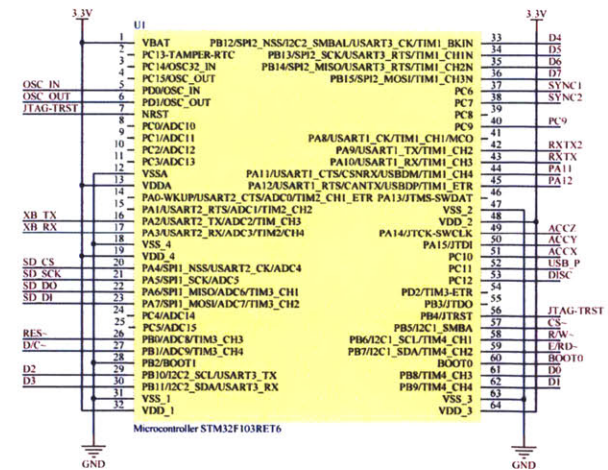
D.



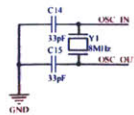
E.



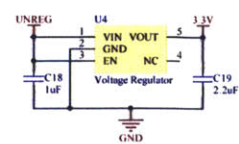
A.



B.



C.



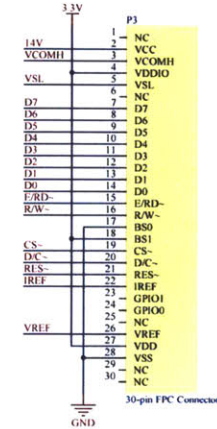
### Screen Circuit + Microcontroller-Screen Interface

The OLED display used in Display Blocks has a 30-pin interface to the microcontroller. 13 of these pins are used to receive data from the microcontroller and display graphics on the screen. Eight more pins are used for data and five for control. The display operates at 14V. Since each face is powered with a lithium ion battery of 3.7V, the display requires a voltage booster circuit to reach the the 14V required. Diagram F details the 30-pin interface to the OLED Display; Diagram G shows the voltage booster used to achieve 14V.

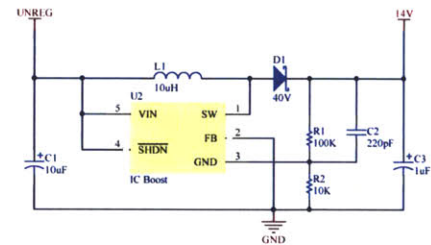
### Microcontroller-microSD Interface

Display Blocks uses a microSD card as the main memory unit for storing video and images. The content of any SD card can be accessed over SPI protocol. To be able to stream video from the SD card, we need a transfer speed of 18MB. The only way to achieve this is to use the DMA functionality that the STM32F103RET6 microcontroller offers. To do so, the SPI interface to the SD card is connected to pins in the microcontroller that are DMA-enabled. An SPI interface is comprised of four logic signals: a clock signal (SCLK), master output/slave input (MOSI), master input/slave output (MISO) and slave select (SS). In Diagram H, we can see the pinout of the micro SDcard holder in the Display Blocks schematics. SD\_CS is the slave select pin, SD\_SCK is the clock pin, SD\_DI is the MISO pin and SD\_DO is the MOSI pin.

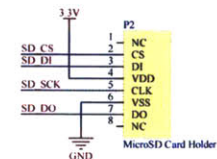
F.



G.



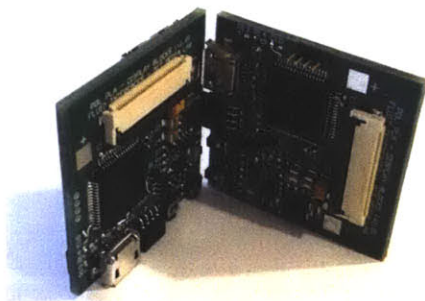
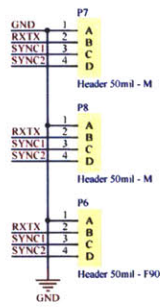
H.



### Microcontroller-Microcontroller Interface

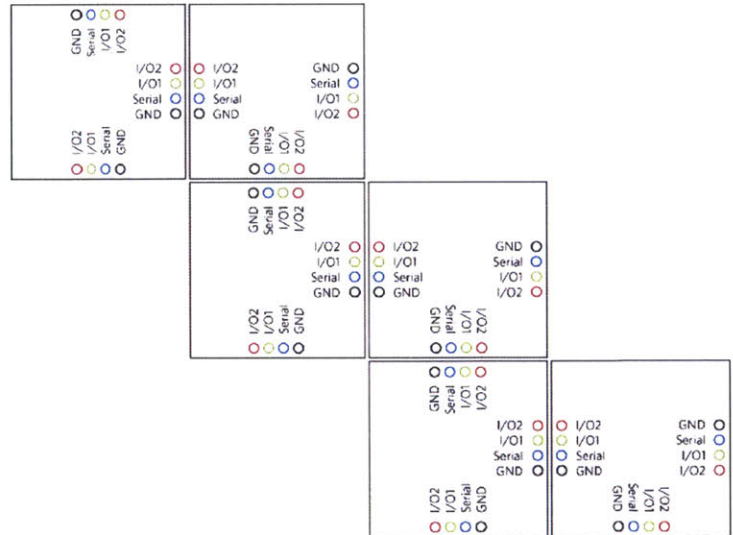
To synchronize the different faces of a Display Block, the microcontrollers for each face share a serial communication bus, two input/output pins and a common ground. The architecture for this bus relies on one of the faces being the master and the rest acting as slaves. By sending commands to the serial bus, the master can tell the other microcontrollers when to display an image or the next frame of a video. In each board, we find three microcontroller-microcontroller interfaces, enabling the boards to be connected in a variety of ways. Diagram J shows how the boards connect to one another. Diagram I details the schematics for three instances of the interface on one of the boards.

I.



▲ Example of connection between two boards.

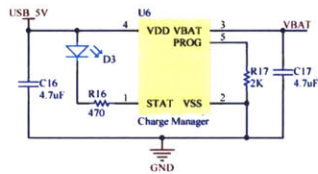
J.



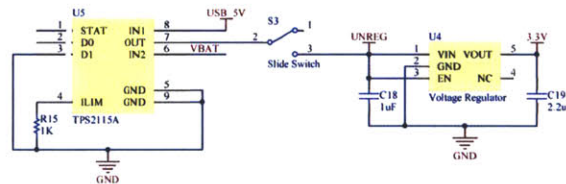
### Power and Battery management system

Each of the faces of a Display Block has its own battery and battery management system. The systems are powered with lithium-ion rechargeable cells. To that effect, each board requires a charge managing circuit (Diagram K). Because it is desirable to be able to power them through USB for debugging, each board has a power selector that prioritizes USB power over battery. Diagram L shows the power selector unit and it connects to the voltage regulator used to power the microcontroller. In between the two devices, there is a switch to turn on and off the entire face.

K.



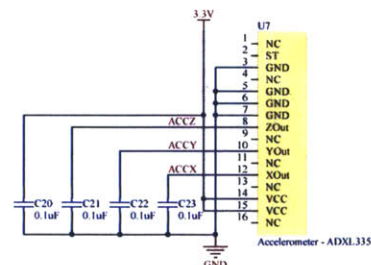
L.



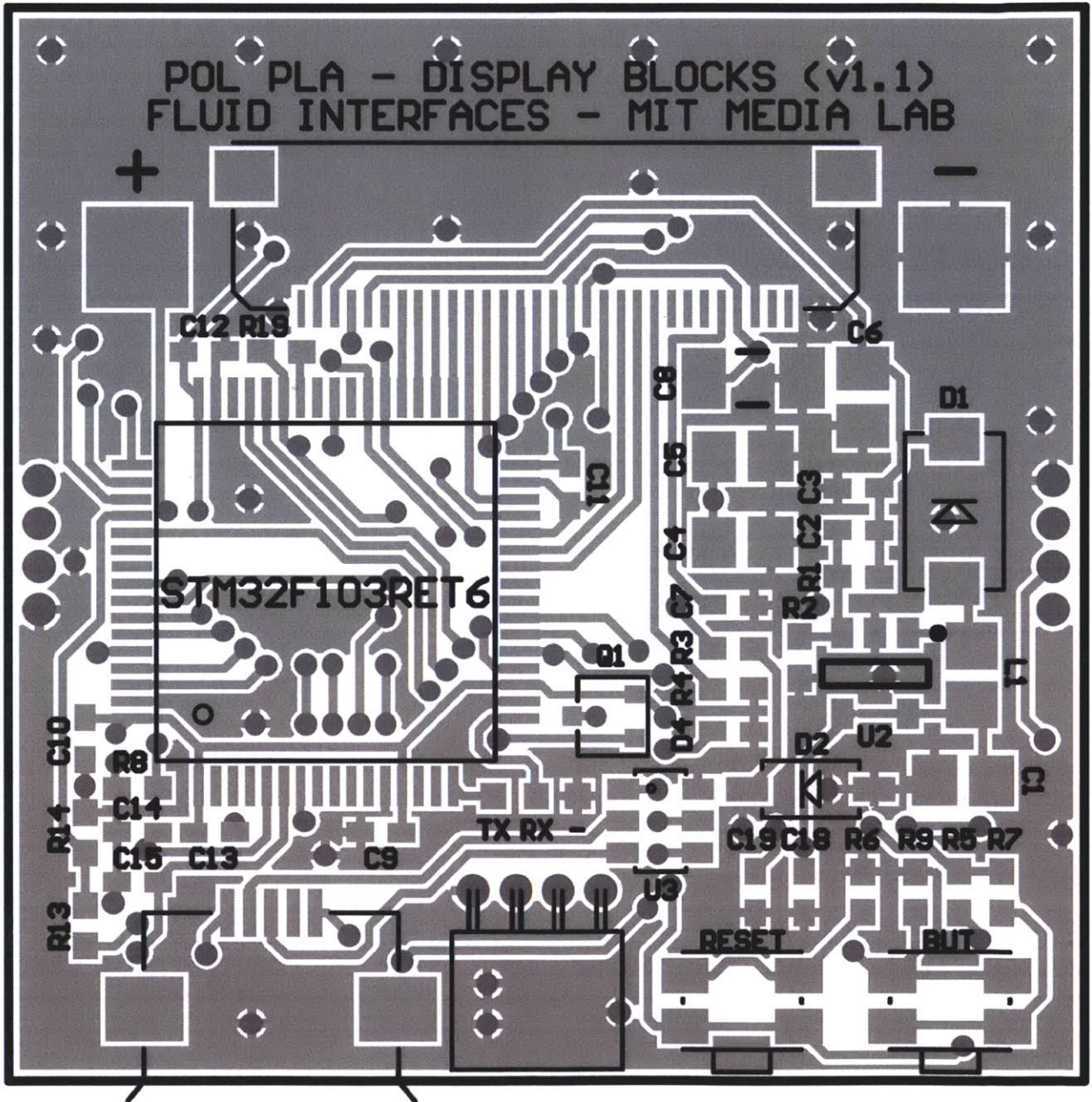
### Microcontroller-Accelerometer Interface

Finally, the microcontroller is connected to a three-axis accelerometer. The accelerometer used, ADXL335, is an analog accelerometer that offers three signals: one for X axis, one for Y axis and one for Z axis. It takes 3.3V to power and some capacitors to reduce the noise of the system. The schematics for the component can be found in Diagram M.

M.

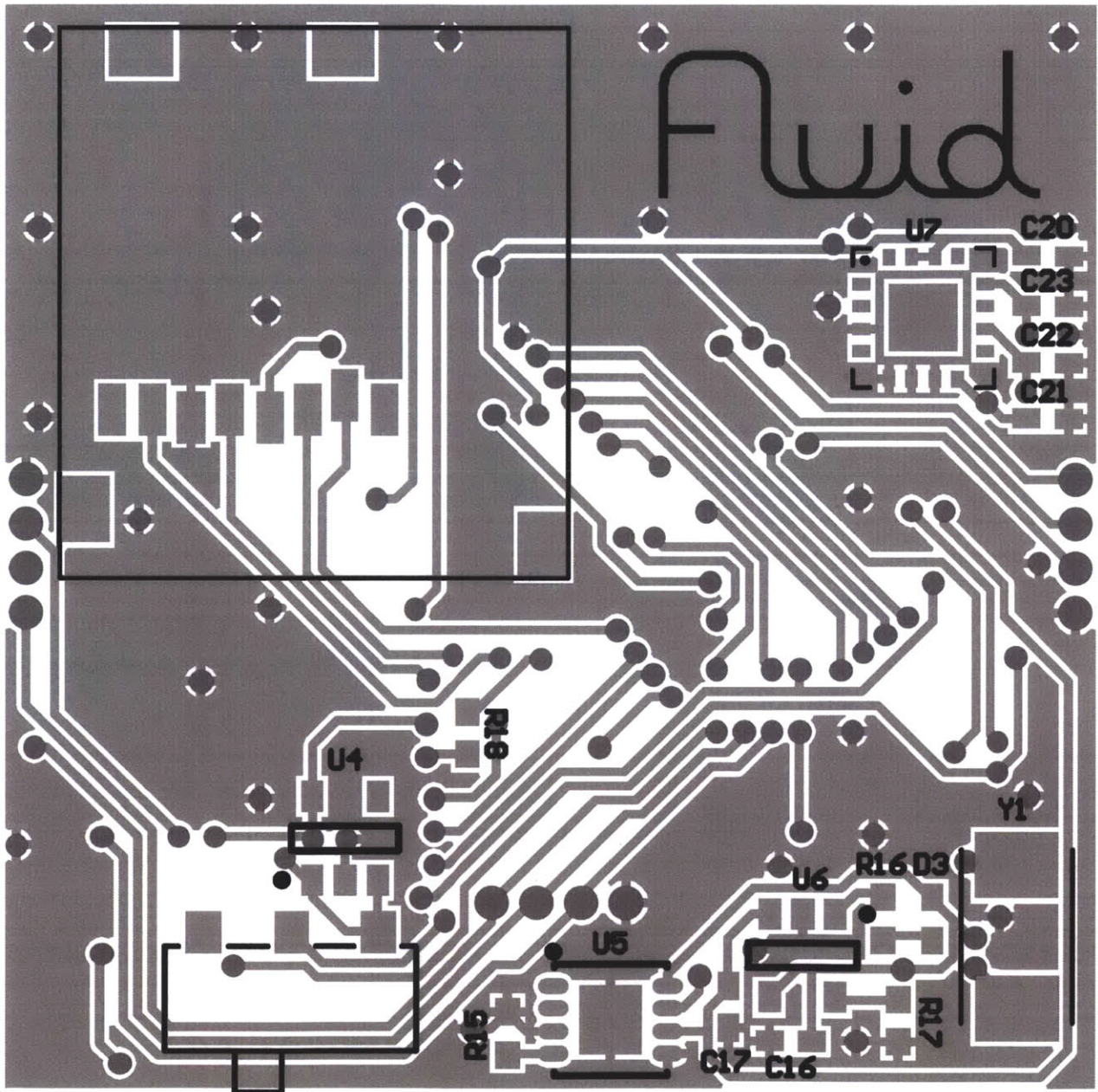


### 3. CIRCUIT BOARD LAYOUT



▲ Top side

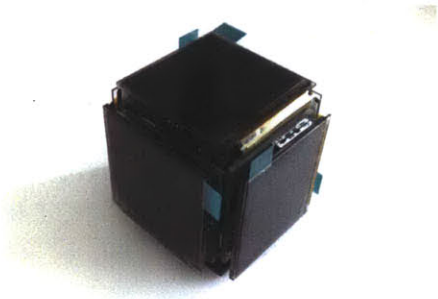




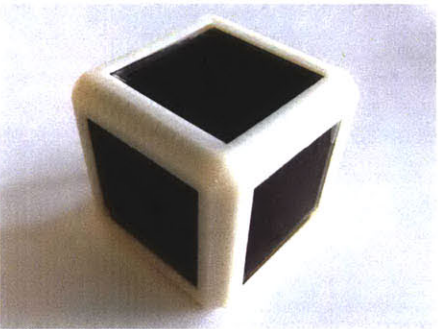
Bottom side ▲

#### 4. ASSEMBLY OVERVIEW

All of the electronic components necessary to populate the circuit on each face of Display Blocks are in surface mount packages, some of them especially small. Despite it being possible to solder manually, I used a manual pick and place machine to position the components, then a heating source to melt the solder into place.



▲ All of the boards assembled into the cube form factor, held together by the connectors.



▲ Final encased prototype.

After assembly, I flashed the Maple bootloader to each microcontroller, enabling further programming using the Maple IDE and the Display Blocks library (Instructions on how to flash the Maple bootloader can be found here: <http://leaflabs.com/docs/bootloader.html>).

After programming all of the boards, I then connected six of to enable synchronization throughout the cube. I did this by using 90-degree-angle 50 mil connectors between the faces. The current design relies on these connectors to arrange the displays in the cubic format, although the connectors themselves are both rigid and fragile.

The final step, after assembling and programming each board, was to put the cubic ensemble carefully inside the casing and to close the top side.





# APPENDIX 2: SOFTWARE

All of the code for Display Blocks is written in C and it is formatted as a library for the Maple IDE. I provide full documentation of the available functionalities.



## 1. LIBRARY REFERENCE

### **void init();**

Initializes the master face. Activates the OLED Display, sets the basic drawing configuration, initializes the SD card memory and sets up the communication with other boards. Only one microcontroller can be the master amongst the many that may share the same communication bus. Failure to comply with this requirement will result in the devices not communicating.

### **void initSlave();**

Initializes a slave face. Activates the OLED, sets the basic drawing configuration, initializes the SD card memory and sets up communication, waiting for instructions.

### **void color(byte r, byte g, byte b);**

Sets the color that any graphics are drawn with. The color is in RGB format; *r* is the red component (from 0 to 63), *g* is the green component (from 0 to 63), *b* is the blue component (from 0 to 63). If this function is not called, the default drawing color is white.

### **void bgcolor(byte r, byte g, byte b);**

Sets the color for the background. The color is in RGB format; *r* is the red component (from 0 to 63), *g* is the green component (from 0 to 63), *b* is the blue component (from 0 to 63). If this function is not called, the default background color is black.

### **void spacing(int fs);**

Sets the spacing between text characters to be displayed on the screen. The spacing is in pixels and it is specified by *fs*.

### **void frameRate(int fps);**

Sets the maximum frame rate, specified by *fps*.

### **void drawBackground();**

Draws the background on the buffer. The background is drawn on top of the buffer, so anything that has been drawn previously without having been refreshed will be lost.



**void drawPixel(byte x, byte y);**

Draws a pixel at the coordinates *x* and *y*. The color of the pixel is set by means of the `color()` function.

**void drawBox(int x, int y, int width, int height);**

Draws a rectangle at the coordinates *x* and *y* from dimensions *width* and *height*. The color of the rectangle is set by means of the `color()` function.

**void drawCircle(int x, int y, int radius);**

Draws a circle at the coordinates *x* and *y* of the specified *radius*. The color of the circle is set by means of the `color()` function.

**void drawCharacter(byte x, byte y, char c);**

Draws a character *c* at the coordinates *x* and *y*. The color of the character is set by means of the `color()` function.

**void drawText(byte x, byte y, char \*text);**

Draws a string *text* at the coordinates *x* and *y*. The color of the font is set by means of the `color()` function.

**void loadImage(char name[]);**

Draws an image from file *name* in screen.

**void loadVideo(char name[]);**

Opens and plays a video from file *name* in screen.

**void playSyncedVideo(char name[]);**

Opens and plays a video from file *name*, also sending synchronization messages through the bus which tells slave microcontrollers to play video simultaneously.

**void refresh();**

Swaps the buffers refreshing the graphics on the screen.

