Build your own cardboard planetarium: A DIY experience for students

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Keywords
Planetarium, DIY, STEAM

Planetariums are usually known as non-formal learning spaces and an incredible way to communicate astronomical and scientific knowledge. However, this potential increases when we build a planetarium because we add knowledge and fun to the space. In this project, we report on constructing a planetarium for this innovative and stimulating learning environment. Currently, there are several models of planetariums, some simpler and others quite complex; however, they are almost always places of passive interaction. Here, we propose to build a cardboard planetarium, which allows a remarkable application of the STEAM strategy in a Do-It-Yourself (DIY) project that can actively involve children from age 12 directly in the construction process. We have designed and built a cardboard planetarium, 4 metres in diameter, with a capacity to host up to 20 children or 10 adults per session. The planetarium is composed of a dome and a base for support; both are constructed from cardboard with different thicknesses due to the individual function of each one. A pilot planetarium was successfully exhibited during a science festival in Portugal. There are plans to build other DIY planetariums in countries across Europe.

Introduction

In a planetarium, people can observe a realistic view of the sky, but as *Plummer et al. (2011)* have noted, the audience of a planetarium session may be able to experience very complex or even impossible sights that cannot be commonly observed. For example, during a planetarium session, it is possible to see the sky from anywhere on Earth, or even in the Solar System, have lines linking the stars to form the constellations, zoom in to any planet to see fine details, or even observe the night sky without the atmosphere, and so on. There are several models of planetariums, from simple pin-hole-based star projectors to state-of-the-art digital projectors. No longer confined to a brick-and-mortar dome, planetariums can be portable, including smartphone apps that allow you to access planetarium software in the palm of your hand. With these, the user can change the view, the date and time, the constellation cultures, or the location on Earth and in the Solar System.

For many schools and astronomy clubs worldwide, the cost to construct a traditional planetarium or to acquire a portable planetarium can be prohibitive; in some cases, the price of this equipment can be higher than a school's annual budget. Do-It-Yourself (DIY) projects engage the public in a fun and educational way. *Hirshon (2020)* cited many DIY projects that practitioners can reproduce at home, in a classroom, office or outreach setting to understand how specific subjects in science work. In fact, when learners work on a team-based DIY project such as the work presented here, they develop a deeper understanding of the subject through hands-on learning and peer teaching: an excellent combination of citizen science and communication.

Why a planetarium?

Astronomy inspires feelings of awe and curiosity, as demonstrated by *Oliveira (2019)*. However, observational astronomy can be difficult to engage with, given the uncertainty of weather and the ever-growing issues of light pollution, particularly in urban areas. The planetarium, therefore, functions as an ideal place to witness a truly dark sky: a dark sky oasis. Inside a planetarium, the operator controls all observational parameters, including clouds, sky brightness, location, and even the presence of an atmosphere. The planetarium provides more opportunities for people to engage with a true dark sky.

According to *Gomes et al. (2017)*, the stimulation and development of non-formal learning opportunities, when added to formal practices, can elevate scientific knowledge in general and specific ways. *Gohn (2014)* noted that non-formal education is an indispensable tool for shaping the citizen. The author cited this tool as independent of the individual's social level of schooling. *Allast et al. (2022)* pointed out that non-formal education is particularly important for young people, as it is less structured and more flexible than formal education, thus influencing the attention and imagination of the youth. Similar results are noticed by *Menezes et al. (2018)*, who analysed data from scientific events about communication and teaching in science.

Furthermore, *Langhi & Nardi (2009)* claim that while astronomy learning can happen in several places, planetariums can be a more effective and scientifically intriguing environment. *Oliveira (2019)* highlights the importance of the planetarium as a place to learn and explore astronomy and science in general for the first time. Planetariums present a unique educational experience: the audience is immersed in a dark room where they stay for a limited time, watching a prerecorded narrative or a live presentation from a trained guide.

DIY planetarium

A DIY planetarium uses low-cost materials and a direct application of STEAM methodology. DIY planetariums have been in development for many decades (e.g., *Watson, 1950; Brozis & Świderski, 2018; Regester & McGahee, 2019*), each demonstrating the benefits of hands-on projects in educational settings with a multitude of different materials and designs.

The STEAM methodology for a DIY planetarium is direct. For example, by planning the construction of a planetarium, learners not only explore concepts from science, mathematics, and engineering but also those of the arts, technology, and innovation. These skills are additionally put to use when creating scripts for planetarium shows. Furthermore, the multidisciplinary nature of astronomy means it is possible to draw on concepts from other fields of science, making the planetarium an ideal place to communicate science (*Langhi & Nardi, 2009; Kukula, 2017; Marques et al., 2021*).

Our cardboard planetarium

The geodesic is a commonly used representation of a sphere using minimal parts. It is defined by its frequency, which is associated with the degree of approximation between a geodesic and a sphere; high frequencies mean less difference. *Regester & McGahee (2019)* explain that this frequency is also proportional to the number of triangles needed to construct the geodesic hemispherical dome and the difficulty of mounting the structure. *Müller (2005)* has an extensive mathematical explanation of the geodesic approximation for constructing domes. Summarising, a geodesic with frequency 1 (1v) uses only four triangles and looks like a pyramid; frequency 2 (2v) geodesics use 30 triangles, producing a decent approximation of a sphere; however, a frequency 3 (3v) geodesic uses 75 triangles, producing a structure similar to the iconic dome of a planetarium. Frequencies 4v and 5v are even better approximations. However, construction becomes increasingly more difficult with increasing frequency. During the planning phase, we tested small-scale geodesics with 2v, 3v, and 4v frequencies. We chose 3v due to its balance between form and mounting difficulty.

There are several materials suitable for building a planetarium. For example, in *Regester & McGahee (2019)*, the authors used a PVC structure and vinyl, and in *Brozis & S´widerski (2018)*, the authors used a parachute as a screen. Each of these activities used the same geodesic frequency described here. In this work, we prioritised cheap and easy-to-handle materials, ultimately deciding to construct our planetarium out of cardboard. Among the various cardboard types possible, we decided to use flat corrugated boards in two different thicknesses, according to the function they would perform in the planetarium structure: dome or base (Figure 1).

In this project, we decided on a planetarium with a diameter of 4.0 metres, which implies an area of 12.36 m^2 on the floor. This dimension is sufficient to allow 20 children, or 10 adults at maximum, in each session. We had the opportunity to test this estimation at the FIC.A festival (Oeiras, Portugal, 10-16 October 2022) at which we held a session with a school class of 19 children (about 8 years old), a teacher and the operator of the planetarium.

The dome

The dome used 3.0 mm thick cardboard cut into two types of isosceles triangles for a total of 75 triangle pieces. The two triangles are described below and graphically represented in Figure 2:

- Triangle X, a base of 81 cm and a lateral edge of 82 cm, a total of 45 triangles
- Triangle Y, a base of 81 cm and a lateral edge of 70 cm, a total of 30 triangles

To connect the triangles, we added tabs to each edge, shown in grey in Figure 2. These tabs must be folded for the assembly step. The dimension of each tab is 2 cm in height along all the triangle's edges. During our

Figure 1 *Photo of the cardboard DIY planetarium mounted, indicating the dome and base.*

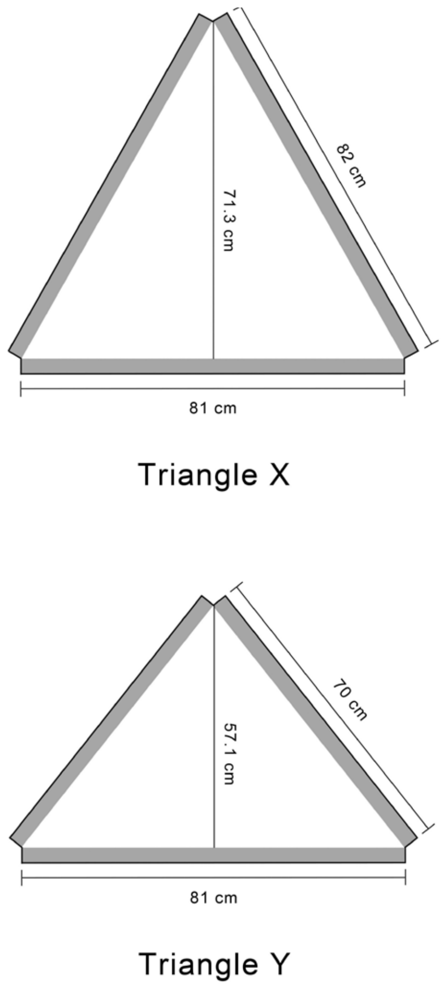

Figure 2: *Schematics of the triangles X and Y and their dimensions. Tabs (used for assembly) are shown in grey.*

planning phase, we tested several methods to join the pieces and found that binder clips were the best solution.

To cut the triangles more easily and ensure they are all the same shape, we created a wood template using a CNC machine. A Computer Numerical Control (CNC) machine processes a piece of tough material to meet specifications by following coded instructions and without a manual operator. In the absence of a CNC machine, the pieces can be cut using a template made from any sturdy material.

The inner part of the dome should be able to reflect the light from the projector, but the natural colour of the cardboard absorbs much of the incident light. Therefore, after the triangles were cut, we painted one face of each one with water-based white paint to mimic the projector screen inside the dome of a stationary planetarium.

The base

To make the base of the planetarium, which supports the dome, we created fourteen 81 x 74 cm rectangles from 5.0 mm thick cardboard. As we did for the dome's triangles, we added tabs on each rectangle edge to facilitate construction. The tabs on the edge of 81 cm were linked with the triangles on the end of the dome, again using binder clips. The final height of the base is 74 cm. This is lower than what might be ideal, however, we were limited by the size of the cardboard pieces. In fact, to build a complete base, it is necessary to use 15 pieces, but we used 14 because one free space would be the planetarium door.

In our previous tests, the base supported the planetarium dome well for three days. After that, we needed to change some rectangles because of the structural stress. This is a portable planetarium, and the structure is designed to be easily constructed and deconstructed for use in multiple locations. Based on our experience, the rectangles that form the base can be reused three times if they are used for less than one day in each iteration. As discussed below, the full planetarium constructed at FIC.A stood for the full week-long festival, providing a rough upper limit to the longevity of the planetarium base.

Assembling our planetarium

To help us during this stage, we decided to label each tab of the triangles with a letter; the sides should only be joined if the letters match. For Triangle X, the base is labelled A and the legs are labelled B. Similarly, for Triangle Y, the base is labelled A, and the legs are labelled C.

The dome assembly used a layer scheme. That is, we connected the triangles to form the central pentagon at the top of the dome and then continued to the next layer. Figure 3 shows the complete scheme of assembling the dome. Each layer approximates a ring of triangles, represented by light (ring 1) and dark (ring 2) grey in Figure 3. This procedure made assembly easier and the links stronger, as we had more time to connect the tabs. Time is an important factor: after starting the assembly process, we needed to construct each ring quickly, as the structure may collapse if the dome stays unbalanced (i.e. if one side is bigger than the other) for a long period of time.

Figure 4 shows the step-by-step process of assembling the dome, which we have also demonstrated in a YouTube video[1]. At the end of the process, the dome has a height of 1.9 metres and a diameter of 4 metres.

Up to this point, two or three people could do the whole process. However, connecting the base to the dome required more help: at minimum, six people. Four people held the dome aloft, and two others connected the bottom of the dome to the rectangles from the base.

The connection of the base must be stronger to support the structure; it is a good idea to reinforce all links between the rectangles with duct tape, for example. In addition, warning tape (e.g., a red and white band) should be placed along the bottom edge of the rectangles on the inside surface of the structure so the audience does not get too close to the wall.

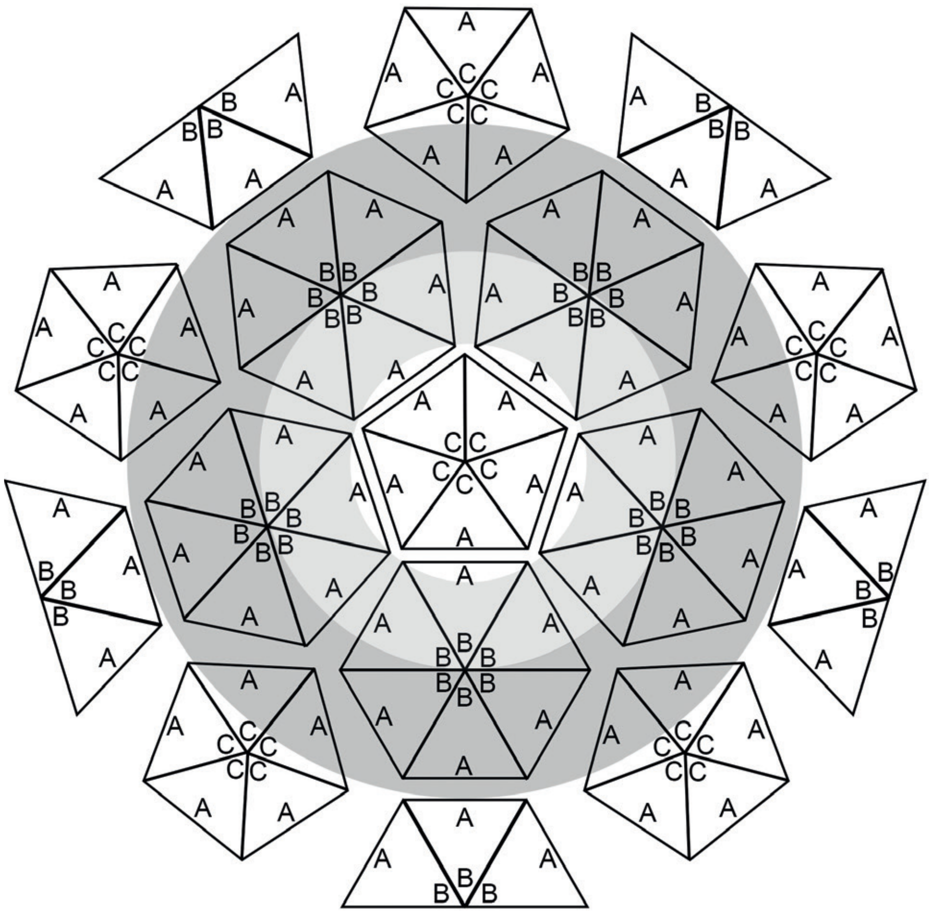

Figure 3: *Assembly scheme of the dome. The triangles from Figure 2 are shown in formation with the construction rings in greyscale.*

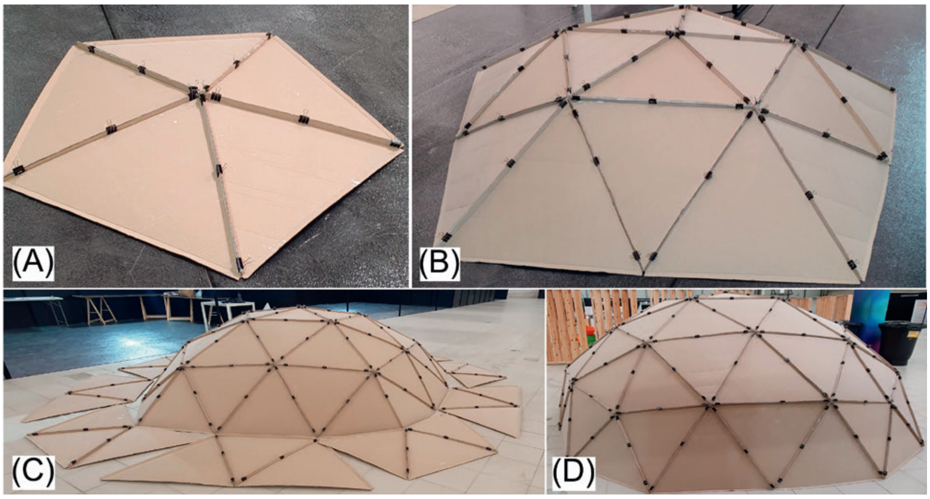

Figure 4: *Step-by-step process of the assembly of the triangles: (A) the central pentagon, (B) adding the first layer, (C) positioning the last layer and (D) the dome mounted.*

The complementary systems

The complementary system comprises two parts: the projector system and the comfort system. Both components require electricity, so the DIY planetarium design must consider this.

The projector system consists of commercial devices, like a laptop, speakers, a projector, DSLR camera lenses, and a custom-built support printed using an ordinary 3D printer. Figure 5 shows this projector system with its two camera lenses. An upcoming article will discuss the projector system, the geodesic approximation used, and the different frequencies possible in depth.

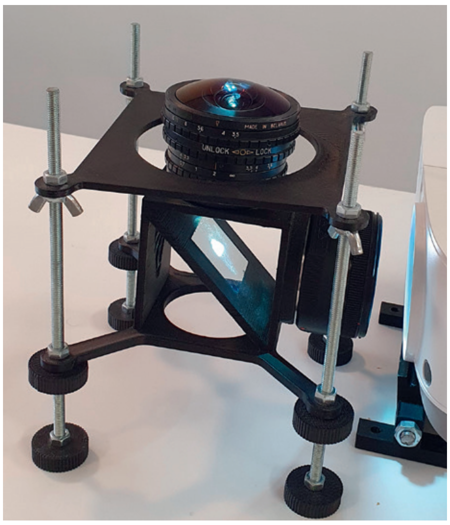

Figure 5: *The projector system that is used inside the cardboard DIY planetarium.*

One of the two lenses has an aperture size of 50 mm and a focal ratio equal to 1.8 (f1.8); the ratio of the focal length of the lens to its aperture), which focuses the light from the projector via a small flat mirror inside the custom-built support. The other is a fish-eye lens with an f3.5. focal ratio and a focal length of 8 mm, which uniformly spreads the light onto the dome's interior. These specifications are necessary to guarantee the correct projection inside the planetarium and the correct optical alignment with the custom-built support used.

We used a 4,000 lumens full-HD LED projector that is sufficient to project a dark sky with a good resolution in the dome. An ordinary laptop installed with Stellarium[2] and VLC[3] was used for the planetarium live session and videos. We chose these because both are open source and available for multiple platforms.

The comfort system consists of a small low-noise fan to keep air moving inside the dome and ensure all inside are comfortable.

The next step: D.O.M.E. Project

During the presentation of our DIY cardboard planetarium in the FIC.A festival in 2022, we noted that many teachers demonstrated intent to replicate this project in their schools, and students demonstrated a genuine interest, too. This result was bigger than we imagined when we started this project. Our idea was simply to show an alternative to a portable planetarium in a DIY project.

Therefore, after this good reception, we decided to implement a formal project with support from the Erasmus+ Programme of the European Union and partnerships in three countries, namely Greece, Ireland and Portugal. We named this the D.O.M.E. Project, an acronym meaning Design your Own Multimedia learning Environment.

This project is divided into two parts, the first of which was the pilot in January 2023. Three Oeiras, Portugal schools built their own DIY cardboard planetarium during their Science Club classes. Students aged between 10 and 16 worked on these prototypes and did a final presentation to the local community in early July 2023.

The next part will start in October 2023, when some schools from each partner country will build a DIY cardboard planetarium and prepare their own planetarium presentation. The final results of this work will be available on the project's website[4], along with all documents necessary to replicate this project in your community, ensuring its sustainability and legacy. We hope this will be a helpful resource, allowing students, teachers, and communities to actively engage in the planetarium experience.

Conclusion

The realisation of the cardboard planetarium project marked a significant achievement in creating an innovative and engaging learning environment for astronomy and scientific exploration — the successful mounting and operation of the planetarium during the week-long[5] FIC.A Festival in Portugal showcased its potential as a dynamic platform for educational outreach. Students aged 8 to 17 from over 20 school classes participated in immersive planetarium sessions. The project effectively demonstrated its ability to captivate and educate a diverse audience.

Even more, the cardboard planetarium project engagement of local schools, where the students created their own planetarium during school time, highlighted the importance of integrating creativity, hands-on learning, and scientific knowledge dissemination. By leveraging the appeal of a DIY project to build a cardboard planetarium, the project effectively offered a tangible and exciting means of imparting complex concepts to learners of all ages. As this initiative gains momentum and inspires the creation of similar projects, this project stands as a beacon of educational innovation and collaboration in astronomy and STEAM education.

Acknowledgements

To the organising committee of the FIC.A festival, the Municipality of Oeiras, the editors and referees of this article, and everyone who, in some way, encouraged or helped this initiative.

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Notes

[1] YouTube link for dome construction: https://youtu.be/iDMfMsSIO24

[2] Stellarium software: https://www.stelarium.org/

[3] VLC software: https://www.videolan.org/vlc/

[4] D.O.M.E. community portal: https://www.dome.nuclio.org/

[5] In the construction presented here, the dome and base structure lasted the entire week-long FIC.A festival. However, we cannot guarantee that the base's structure from the same design will hold longer than that. Refer to Note 4 for other designs from the D.O.M.E. project.

Biographies

Vinicius de Abreu Oliveira has a PhD in physics and astrophysics from the Federal University of Santa Maria (2009), Brazil. He has much experience as a professor and researcher in astronomy, physics and space geoscience. In 2015, Vinicius started to work in astronomy outreach, using a mobile planetarium. Since 2022, he has worked as the Project Manager at NUCLIO in Portugal.

Frances McCarthy is the Education & Outreach Officer at MTU Blackrock Castle Observatory. She studied physics and astronomy at the University of Toronto, Canada. She has worked in formal and informal education environments in Canada, the UK and Ireland and develops and delivers education workshops and activities for all ages. She has worked in planetariums since 1984, at European Small and Portable Planetarium Conferences and the annual conference of the British Association of Planetaria.

Niall Smith studied astrophysics at the University College Dublin. He lectured in the Department of Applied Physics & Instrumentation at Cork Institute of Technology for 18 years before becoming the Institute's first Head of Research in 2005. In 2020, he was awarded the SFI Research Image of the Year for work on using astrophysics techniques to determine the efficacy of masks against Covid-19.

Priscila Doran has an MSc in biology and is a certified trainer. She coordinates interdisciplinary projects that connect art and science and collaborates on the creative design of NUCLIO's dissemination material.

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Gustavo Rojas has a PhD in astrophysics from USP, Brazil. He has worked as an astrophysicist at São Carlos Federal University, Brazil, and since 2012, he has been a member of the organising committee of the Brazilian Astronomy and Astronautics Olympiad (OBA). Additionally, he has acted as the team leader of the International Olympiad on Astronomy and Astrophysics (IOAA) for Brazil and Portugal.

Rosa Doran has a PhD in Science Education from the University of Coimbra and is a certified trainer by the Scientific and Pedagogical Council of Continuous Training (University of Minho, Portugal). She is the president of the executive council of the Global Hands-on Universe Association, the chair of the Galileo Teacher Training Program, the vice-chair of the panel of education of COSPAR, and the co-chair of the IAU/PLOAD.