



UNIVERSIDADE D
COIMBRA

Natália Soares Magalhães

EXPLORATION OF THE PHYSICAL DIMENSION
OF INFORMATION VISUALIZATION FOR
AWARENESS CAMPAIGNS

Dissertation in the context of the Master in Design and Multimedia, advised by
Professor Evgheni Polisciuc and Professor Tiago Cruz and presented to the
Department of Informatics Engineering of the Faculty of Sciences and Technology
of the University of Coimbra.

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EXPLORAÇÃO DA DIMENSÃO FÍSICA DE VISUALIZAÇÃO DE INFORMAÇÃO PARA CAMPANHAS DE SENSIBILIZAÇÃO

**Dissertação no âmbito do Mestrado em Design e Multimédia, orientada pelo
Professor Evgheni Polisciuc e Professor Tiago Cruz e apresentada ao
Departamento de Engenharia Informática da Faculdade de Ciências e
Tecnologia da Universidade de Coimbra.**

Setembro 2025

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Abstract

Information visualization has been an important tool to reveal hidden patterns in complex data and communicating these findings with many audiences. Data physicalization also offers a promising alternative by representing information through tangible artifacts, enabling more accessible experiences for broader audiences. This dissertation explores the intersection of information visualization and data physicalization in an awareness campaign using space debris as a case study. Despite the risk of collisions, orbital debris remains largely invisible to the public, who rely on satellites for everyday tasks like navigation, telecommunications, and weather monitoring. To address this, we intend to explore how physical artifacts can be used for awareness and engagement. Our experiments include 3D-printed charts, tactile maps, wearable objects, and data sculptures that transform raw datasets into tangible forms. Beyond presenting prototypes, this dissertation also consolidates a reproducible pipeline that links the dataset selection and preprocessing to physical encoding, fabrication strategies, photographic documentation, and the creation of campaign materials. Throughout, constraints such as scale, durability, production time, and cost are treated as design parameters rather than afterthoughts.

Keywords

Data Physicalization, Information Visualization, Awareness Campaign, Space Debris

Resumo

A visualização de informação tem sido uma ferramenta importante para revelar padrões ocultos em dados complexos e comunicar essas descobertas a diferentes públicos. A fisicalização de dados também oferece uma alternativa promissora, ao representar a informação através de artefatos tangíveis, permitindo experiências mais acessíveis para públicos mais amplos. Esta dissertação explora a interseção entre visualização de informação e fisicalização de dados em uma campanha de sensibilização, utilizando o lixo espacial como estudo de caso. Apesar do risco de colisões, os detritos orbitais permanecem amplamente invisíveis para o público, que depende de satélites para tarefas cotidianas como navegação, telecomunicações e monitoramento meteorológico. Para lidar com isso, pretendemos explorar como artefatos físicos podem ser usados para promover conscientização e engajamento. Nossos experimentos incluem gráficos impressos em 3D, mapas táteis, objetos vestíveis e esculturas de dados que transformam conjuntos de dados brutos em formas tangíveis. Para além da apresentação de protótipos, esta dissertação também consolida um pipeline reproduzível que conecta a seleção e o pré-processamento de dados à codificação física, às estratégias de fabricação, à documentação fotográfica e à criação de materiais de campanha. Ao longo do processo, restrições como escala, durabilidade, tempo de produção e custo são tratadas como parâmetros de design, e não como meros fatores secundários.

Palavras-Chave

Fisicalização de Dados, Visualização de Informação, Campanhas de Sensibilização, Lixo Espacial

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Chapter 1

Introduction

1.1 Motivation

Information visualization has been a useful tool for understanding complex data and communicating insights to different audiences. [Spence, 2001]. From early cartographic representations to sophisticated interactive dashboards, being able to visually parse information has helped to identify patterns and trends and make more informed decisions. More recent advancements in technology are allowing new ways to represent information beyond static charts, such as interactive web visualizations that let readers filter, zoom, and identify patterns and trends in the data, some ambient and embedded displays can also bring information into everyday spaces, fabrication workflows such as 3D printing and laser cutting also make it possible to create data sculptures, tactile maps, interactive objects and even wearables that can be handled, compared, and discussed.

Within Human-Computer Interaction, the shift from pixels to artifacts is formalized through tangible interfaces and the physicalization of data. Here, material properties, such as shape, weight, texture, light, and motion, act as encodings alongside position and color, providing new ways to view data and make experiences more engaging, memorable, and accessible to broader audiences [Jansen et al., 2015]. This view treats making as part of the analysis: the choice of material, scale, and mechanism is not only aesthetic, but affects legibility, engagement, and what comparisons become easy or hard.

Data physicalization aims to represent information in tangible, physical forms [Jansen et al., 2015] so people can see, feel, and manipulate data. These encodings can utilize multiple senses (vision, touch, and even sound, smell, or taste) and transform reading into a bodily activity rather than just a visual one. In tangible interaction, this is framed as bridging bits and atoms: the form of the object becomes part of the interface and the message [Ishii, 1997].

In practice, data physicalization can take many forms:

- **Static / passive:** fixed data sculptures, tactile maps, layered stacks;

- **Dynamic / active:** actuated pieces whose form, light, or motion change with data;
- **Augmented / hybrid:** physical bases that uses projection or augmented reality;
- **Rearrangeable / modular:** sets of tokens or tiles that can be sorted, stacked, and recomposed with user interaction;
- **Interactive:** mechanisms or electronics that respond directly to user manipulation;
- **Embedded / material:** objects whose material or structure intrinsically encode the data;
- **Personal:** artifacts built from one's own data to support reflection.

Many projects utilize digital fabrication techniques (such as 3D printing, laser cutting, and CNC) in conjunction with simple electronics to create hybrid artifacts that facilitate handling and spark conversation. They show what screens cannot: weight, thickness, temperature, and texture. Allowing people to pick up parts, stack, align, and feel them. At the same time, these fabrication methods have their own set of constraints: precision, scale, fabrication time, durability, and accessibility. So the choices of material, size, and mechanism will directly determine legibility and interaction [Jansen et al., 2015].

Although the principles of information visualization (mapping, hierarchy, scale, contrast) strongly influence data physicalization, they differ in how they engage perception and action. Screen-based graphics rely on visual pattern recognition. Physicalizations invite touch, manipulation, and spatial memory; they can also be static and read only by sight. However, the object's presence changes the experience because the viewer can change their viewpoint or distance. This embodied perspective often makes the message more memorable and relatable, especially when the goal is to spark conversation, teach a concept, or communicate [Dragicevic et al., 2019].

At the same time, there is a growing demand for effective science communication, especially in areas that may feel abstract or distant but can have enormous consequences, such as space debris. In the mid-20th century, the launch of the first artificial satellites represented an important milestone in our history and space exploration. However, decades later, Earth's orbital environment has become increasingly crowded, now containing more than 35,000 objects, including non-functioning satellites, rocket bodies, fragmentation debris, and other space debris. The accumulation of these objects raises fears of a cascade effect known as the Kessler Syndrome, in which collisions between objects spawn more debris, increasing collision probabilities and creating a chaotic scenario for future missions and communications on Earth [Kessler et al., 2010].

Space debris is a considerable threat to operational satellites and future missions. Much of our modern society relies on these orbital infrastructures, such as satellites for global positioning systems (GPS), telecommunications, Earth observa-

tion, weather forecasting, and more [Nasa, 2017]. Any damage to this infrastructure can cause disruptions to essential communication services and slow scientific and commercial space exploration. Despite such high stakes, the concept of orbital debris remains distant to the general public due to its invisibility in our daily lives. Satellites and debris orbit hundreds to thousands of kilometers above our heads, well beyond everyday perception. Therefore, an important question arises: How can we increase awareness of such an "invisible" threat?

With this question in mind, we propose to explore the intersection of information visualization, data physicalization, and awareness campaign, using space debris as a case study. The goal is to create a physical object or set of physical objects that communicate data about orbital debris, sensibilizing audiences to engage with the problem in a more tangible, memorable, and impactful way. By investigating how individuals perceive and interact with a physical artifact representing these "hidden" threats, this dissertation hopes to elevate public perception about the urgency of mitigating the issue of space debris.

1.2 Context

From the earliest days of the Space Race, humanity has been sending satellites and rockets into Earth's orbit [Nasa, 2017]. What began as a race for scientific prestige and geopolitical power during the Cold War has become a competition and commercial enterprise, with states and companies launching thousands of objects each year. Many of these satellites and rocket bodies eventually stop working yet remain in orbit as space debris (Figure 1.1). Some re-enter Earth's atmosphere and burn up, but many persist for years and decades.

Space debris is not limited to large defunct satellites. Tiny shards, like paint flecks or small pieces of metal, can also cause substantial damage when moving at orbital velocities of around 7 km/s or more [Nasa, 2017]. These smaller fragments are often byproducts of collisions, explosions, or disintegration of larger space objects. Each collision creates even more fragments, thus fueling a self-perpetuating cycle that can be understood as the Kessler Syndrome [Kessler et al., 2010].

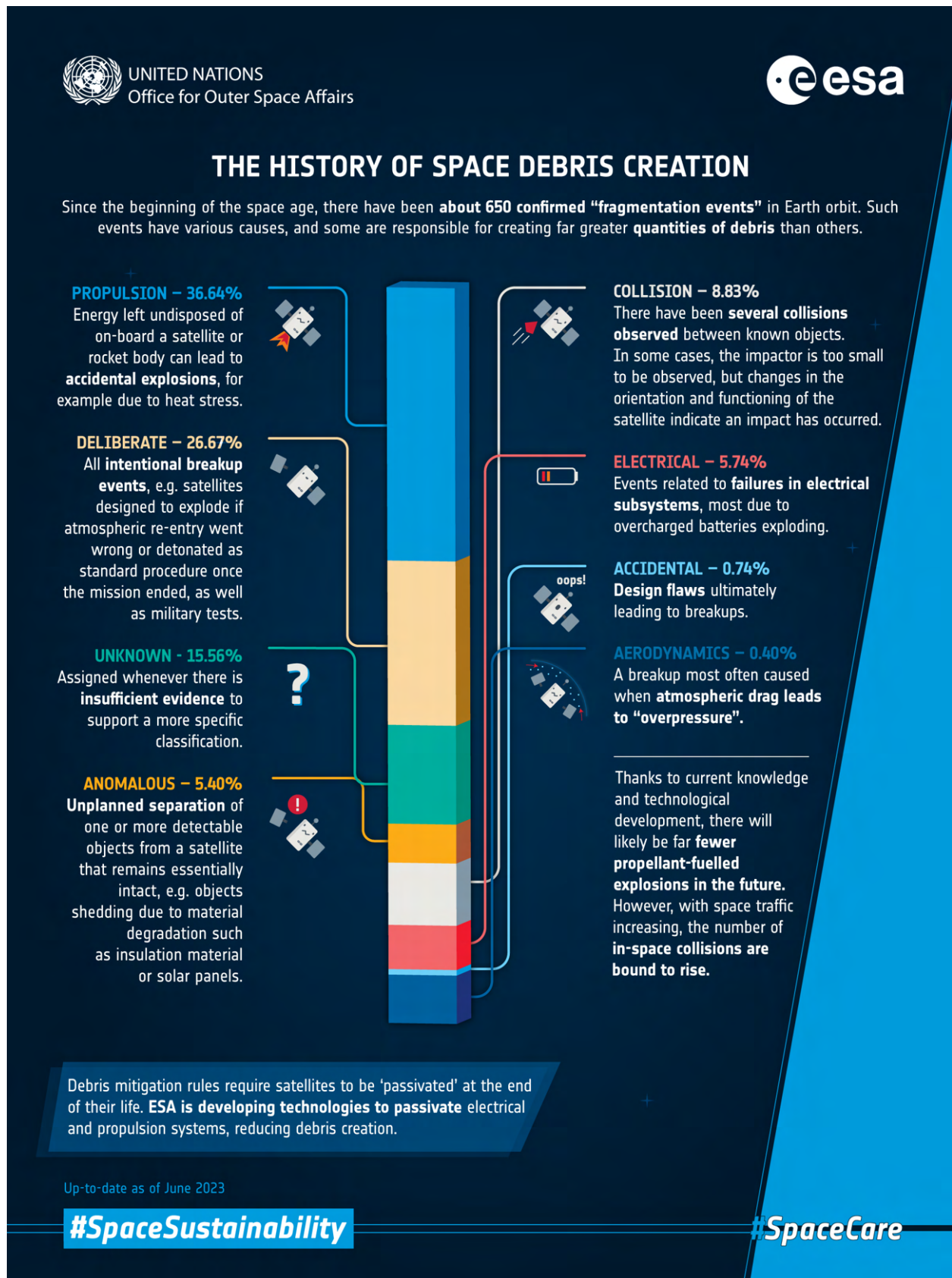


Figure 1.1: History of Space Debris (adapted from [Stasko, 2018])

We rely on satellites for everything from GPS-based navigation, weather fore-

casting, finance, telecommunication, and beyond [Wang, 2010]. Losing satellites to collisions can have immediate cascading effects on terrestrial infrastructures.

Removing debris from orbit is difficult and expensive and has become a hot topic recently, with prototypes being tested. These efforts are still in their infancy, and the scale of the problem continues to grow [Stasko, 2018].

Despite the gravity of these concerns, many people remain unaware of how congested Earth's orbit has become or how reliant we are on satellites. One reason for this lack of awareness is that the problem feels physically remote: collisions or near-misses in space don't catch our attention in the same way that polluted oceans or deforestation do. Indeed, images of space debris are far less common and mostly computer-generated, which can lead to a sense of complacency as the issue appears "far away." Visually speaking, the night sky still looks much the same as it did centuries ago, masking the magnitude of the problem orbiting above us.

This gap in public awareness highlights the crucial role that information visualization can play. By simplifying complex phenomena and presenting them in clear, engaging ways, visual tools make data more understandable for both experts and general audiences. Whether through charts, graphs, maps, or interactive dashboards, well-designed data visualizations can bridge the disconnect between our everyday experiences and the invisible challenges we face in space.

Data physicalization, which is another powerful tool for visualization and communication, pushes these principles into the three-dimensional and tactile realms, aiming to explore the capacity of human cognition beyond the visual channel [Jansen et al., 2015]. In data physicalization, artifacts encode data in physical attributes such as transparency, viscosity, weight, light absorption, sometimes even integrating sound or scent [Hornecker and Buur, 2006]. Researchers have noted that tangible artifacts can enhance data comprehension, memorability, and emotional engagement [Ishii, 1997].

Raising public awareness about global challenges is a mission of many governmental and non-governmental organizations. Whether data-driven or otherwise, visualization can be a powerful tool in science communication strategies. When done well, it goes beyond mere illustration to offer insights, it shows overlooked aspects of a problem or even catalyzes emotional responses and policy changes [TruthandBeauty, 2022].

The reach and effectiveness of visual content depend on design decisions. Awareness campaigns are not just about providing "precise" or "truthful" data, they also need to address the emotional, social, and contextual dimensions of learning. By focusing on space debris, the matter of objects orbiting Earth brings the problem down to Earth, making people think and perceive the scale of the problem.

Nevertheless, designing physicalizations brings new challenges compared to designing digital charts. Factors such as material choice, weight, texture, color, shape, mechanical movement, and more become an integral part of the encoding of data variables. A slight modification in scale or color might change how a user interprets numerical values and receive the message in general. These is-

sues create more steps in the design process and open up more creativity and user engagement possibilities.

1.3 Objectives

The primary goal of this project is to develop a data physicalization artifact, or set of artifacts and elaborate an awareness campaign around them to represent space debris data in a clear manner for general audiences, thereby raising awareness about the importance of mitigating space debris and its impacts on both space infrastructure and everyday life. The process involves identifying ways of physical encodings for the data to fabricate the artifact(s).

Secondary Objectives

- Elaborate an awareness campaign;
- Explore data physicalization techniques to represent complex datasets.
- Simplify and select the most relevant data for public audiences, ensuring ease of understanding.
- Create visual materials for the awareness campaign;

1.4 Outline

- **Chapter 1: Introduction**
Presents the overall context, motivation, and objectives of the project.
- **Chapter 2: Methodology and Planning**
Outlines the project schedule, milestones, and key tasks.
- **Chapter 3: Literature Review**
Present the main concepts about the themes of this dissertation, such as information visualization, data physicalization, and awareness campaign.
- **Chapter 4: Related Work**
Examines existing projects and case studies in data physicalization and information visualization.
- **Chapter 5: Preliminary Work**
Describes the initial experiments in data gathering, analysis, and early prototypes, discussing lessons learned and areas for improvement.
- **Chapter 6: Design Iterations and Final Object**
Documents the iterative prototypes (zoetrope, Orbital Debris Iris, Speed Track) and the final Trash Mountain, including encoding choices, fabrication, and discussion.

- **Chapter 7: Awareness Campaign**

Presents the campaign concept and materials (infographics, posters, stickers, tote bags), outlining process and reflection on consistency and audience impact.

- **Chapter 8: Conclusion**

Synthesizes the main contributions, limitations, and directions for future work.

Chapter 2

Methodology and Planning

In this chapter we present the methodology that was adapted to the needs of the project, as well as the work plan for the entire academic year.

2.1 Methodology

The methodology adopted in this thesis is Design Science Research (DSR), a practice-oriented approach used in fields that involve the creation of solutions and evaluating their impact. Unlike pure theoretical or observational methods, this framework emphasizes iterative design, implementation, and assessment cycles, making sure that each artifact developed uses user feedback and is ingrained in a concrete problem [Hevner et al., 2010]. This methodology fits the framework of this dissertation because the main goal is not just to analyze space debris data but to create physical artifacts that effectively communicate this and create an awareness campaign for it.

Design Science Research emphasizes constructing and refining artifacts through iterative prototyping. We can validate whether a chosen scale, shape, or color encoding conveys the intended information by repeatedly testing these prototypes.

This approach also ensures that the development of the artifact does not end with only the fabrication of the artifact. An integral step is an evaluation, which can involve informal user observations, interviews, or surveys to ascertain how effectively participants understand the insights about orbital debris after encountering the physical objects and if the campaign communicates effectively.

The guidelines of Design Science Research are as follow:

1. **Design as an Artifact:** Design-science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation. Here, the artifact created is a stacked-cube sculpture, a (*Trash Mountain*) that encodes temporal accumulation.
2. **Problem Relevance:** The objective of design-science research is to develop technology-based solutions to important and relevant business problems.

Here, the problem is public awareness of orbital debris (with emphasis on secondary-school students), so design choices were constrained by legibility at viewing distance, fabrication, and the clarity of the campaign message.

3. **Design Evaluation:** The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods. User tests were planned to validate the encodings and messages, but were not executed due to time constraints.
4. **Research Contributions:** Effective design-science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and/or design methodologies. This work provides a concrete example of an awareness piece, a documented mapping pipeline from satellite data to a tangible form, and campaign materials derived from the object.
5. **Research Rigor:** Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact. Rigor is maintained by describing datasets and processing, making the process of transforming data into an object where its geometry, size, aggregation mapping is explicit, and documenting constraints so decisions are traceable.
6. **Design as a Search Process:** The search for an effective artifact requires utilizing available means to achieve desired ends while satisfying the laws of the problem environment. In this dissertation, the search ran in short iterations with explicit criteria. Alternatives were built, tested, and then discarded or refined. This process converged on a simpler, more readable physical encoding aligned with the campaign.
7. **Communication of Research:** Design-science research must be presented effectively both to technology-oriented as well as management-oriented audiences. The artifact was photographed and translated into posters, billboards, and infographics that supply context and scale for the campaign, aligning the object with a public, non-expert audience.

2.2 Work plan

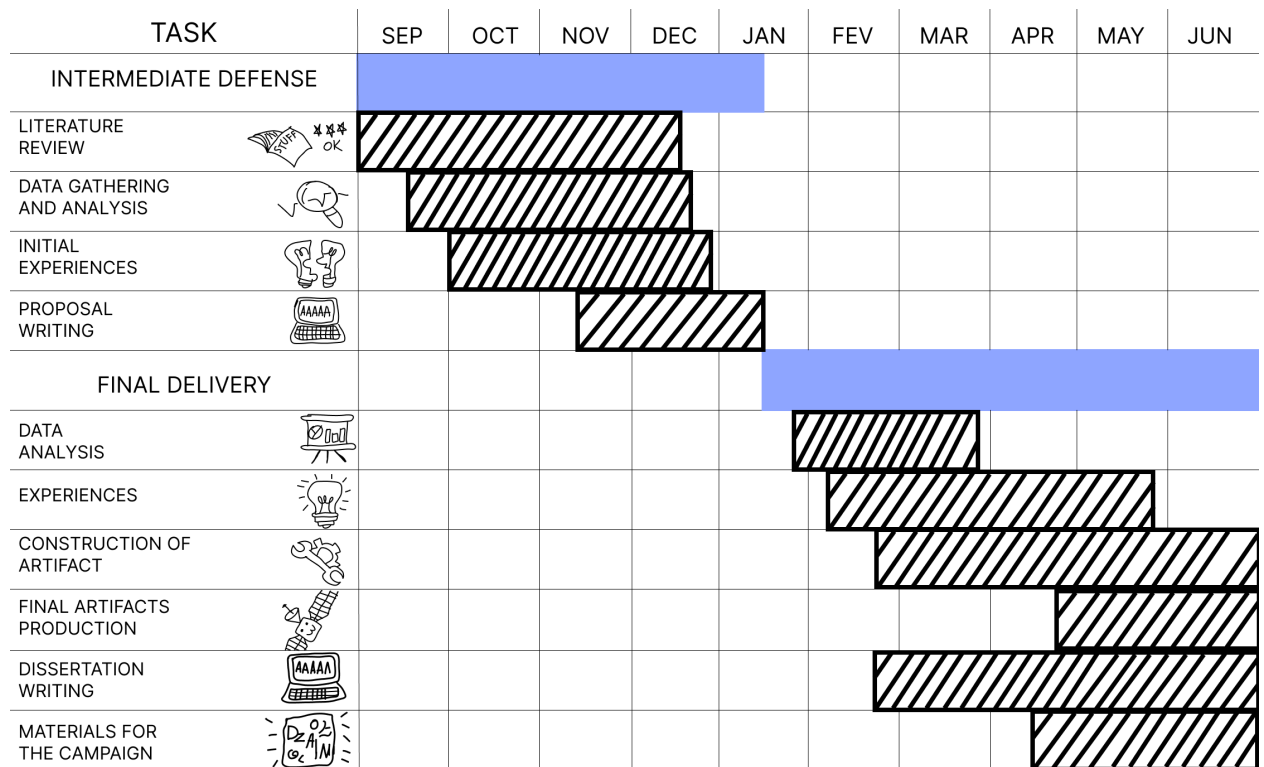


Figure 2.1: Work Planning

The work plan is organized around key tasks starting from September through June. There are two main milestone periods, the Intermediate Defense and the Final Delivery, both include what activities will be done during those phases. The work plan is depicted in Figure 2.1.

Activities of Preparatory Work:

- **Proposal Writing:** Craft the proposal document, where the entire process will be laid out and explained in detail.
- **Data Gathering and Analysis:** Collect data on satellites and space debris, assess whether the data sources are reliable and suitable for exploration, and examine formats and dataset structures. Conduct initial analyses to uncover patterns, relationships, and potential areas of interest in the data.
- **Literature Review:** Read academic articles, books, and thesis related to data physicalization, data visualization, awareness campaign, and space debris, to ensure a solid theoretical foundation for the project.
- **Initial Experiences:** Use a 3D printer (or other rapid prototyping techniques) to create exploratory objects based on the initial data findings. The goal here is to get a feel for possible representations, without finalizing any designs. These prototypes help reveal which ideas and relationships might be worth pursuing further.

Activities of the Final Delivery

- **Data Analysis (Refinement):** Conduct deeper, more rigorous data exploration, potentially using a new dataset and additional visualization tools like D3.js, not just Python, to create more flexible visualizations.
- **Experiences (Iteration):** Unlike the initial experiences, this phase involves more deliberate experimentation, keeping interaction, form factor, and the final product in mind. Prototypes will be created with a more clear vision of the end result.
- **Construction of the Artifact:** Begin building the final artifact(s) with a clear focus on how it will ultimately look and function.
- **Final Artifact Production:** After integrating the findings from validation tests, finalize and construct the polished artifact(s), ensuring all design refinements are in place.
- **Dissertation Writing:** Continue writing and updating the thesis, incorporating new experiences, evaluations, and processes that emerged during the final phases.
- **Materials for the Campaign:** With the artifact nearly complete, develop additional outreach materials, such as flyers, posters, or tote bags, for the awareness campaign.

Comparing what was initially planned with what was ultimately produced, the project did not require D3 since there was no need for an interactive or more flexible visualization. User tests were scheduled to shape the final artifact, but they were not conducted. Halfway through the project, the scope shifted from one artifact to three (each highlighting a different aspect of the data for the campaign). However, technical issues and time constraints made that expansion unfeasible, so the work converged back to a single artifact. That choice, along with the fabrication workload, eliminated the testing time window. The final artifact was created without any user input and was not tested. Most of the effort was spent on making and iterating, the experimentation phase only closed near the end. This dissertation, above all, documents the experimentation of ways to convey data in physical form.

Chapter 3

Literature Review

This chapter will present the main concepts related to the topics covered in this thesis proposal: information visualization, data physicalization, visualization in the context for awareness campaign and Digital Fabrication.

3.1 Information Visualization

Information visualization transforms abstract data into visual representations that can be easily understood allowing the user to explore, analyse and better understand complex information and their relationships [Spence, 2001]. In this field, raw data is transformed into visual representations for exploration, analysis, or communication. Terms such as "Data Visualization" or "Information Visualization" refer to "the use of computer-supported, interactive, visual representations of abstract data to amplify cognition" [Card et al., 1999].

Abstract data has no inherent spatial structure [Telea, 2014], some examples of this kind of data can be results of a survey, Inflation rates or GDP growth percentages, Human Development Index (HDI) scores, population age distributions. Making one of the main challenges in Information Visualization to find effective mapping techniques between abstract entities and spatial representations [Jacko and Stephanidis, 2003]

Ware [2019] list some of the many advantages of data visualization:

- Understand large amounts of data;
- Perception of properties that are not anticipated;
- Identification of problems with the data itself, such as detecting anomalies or outliers;
- Understanding of both large and small amounts of data;
- Generation of hypotheses related to the data.

It's a bridge between raw data and the cognitive processes required to have meaningful insights about this data. Unlike textual or tabular data, visualizations make these insights more intuitive. For example, when data is presented in a table the viewer needs to scan every row and column to identify patterns and look for points of relevance. By contrast, a graphical representation of box office revenue (Figure 3.2) can be more intuitive than a table containing the same data (Figure 3.1).

Rank	Release	Gross	Theaters	Total Gross	Release Date	Distributor
1	Top Gun	\$176,781,728	1,531	\$176,781,728	May 16	Paramount Pictures
2	Crocodile Dundee	\$116,849,307	1,495	\$174,803,506	Sep 26	Paramount Pictures
3	The Karate Kid Part II	\$115,103,979	1,610	\$115,103,979	Jun 20	Columbia Pictures
4	Back to School	\$91,258,000	1,751	\$91,258,000	Jun 13	Orion Pictures
5	Aliens	\$85,160,248	1,454	\$85,160,248	Jul 18	Twentieth Century Fox
6	The Color Purple	\$83,993,103	1,109	\$94,175,854	Dec 20	Warner Bros.
7	Star Trek IV: The Voyage Home	\$72,742,016	1,956	\$109,713,132	Nov 26	Paramount Pictures
8	Ruthless People	\$70,788,212	1,114	\$71,624,879	Jun 27	Walt Disney Studios Motion Pictures
9	Out of Africa	\$70,365,426	1,102	\$87,071,205	Dec 20	Universal Pictures
10	Ferris Bueller's Day Off	\$70,136,369	1,330	\$70,136,369	Jun 11	Paramount Pictures
11	Down and Out in Beverly Hills	\$58,093,661	1,084	\$62,134,225	Jan 31	Walt Disney Studios Motion Pictures
12	The Color of Money	\$52,293,982	1,205	\$52,293,982	Oct 17	Walt Disney Studios Motion Pictures
13	Stand by Me	\$52,287,414	848	\$52,287,414	Aug 8	Columbia Pictures
14	Legal Eagles	\$49,851,591	1,248	\$49,851,591	Jun 20	Universal Pictures
15	Cobra	\$49,042,224	2,131	\$49,042,224	May 23	Warner Bros.
16	The Jewel of the Nile	\$46,166,472	1,490	\$75,973,200	Dec 13	Twentieth Century Fox
17	Police Academy 3: Back in Training	\$43,579,163	1,788	\$43,579,163	Mar 21	Warner Bros.
18	The Golden Child	\$43,144,576	1,714	\$79,817,937	Dec 12	Paramount Pictures
19	Peggy Sue Got Married	\$41,382,841	1,107	\$41,382,841	Oct 10	TriStar Pictures
20	Poltergeist II: The Other Side	\$40,996,665	1,599	\$40,996,665	May 23	Metro-Goldwyn-Mayer (MGM)
21	Short Circuit	\$40,697,761	1,310	\$40,697,761	May 9	TriStar Pictures
22	Pretty in Pink	\$40,471,663	1,117	\$40,471,663	Feb 28	Paramount Pictures

Figure 3.1: Table representation of Domestic box Office in 1986 (adapted from [BoxOffice, 1986])

Visualizations explore the strengths of human visual perception, when engaging with a visualization, the viewer go through a process that involves three phases (Figure 3.3): perceiving, interpreting, and comprehending [Kirk, 2019]. These phases culminate in the communication experience. To achieve this communication in an effective way, it's important to address the challenges of transforming information into visual forms.

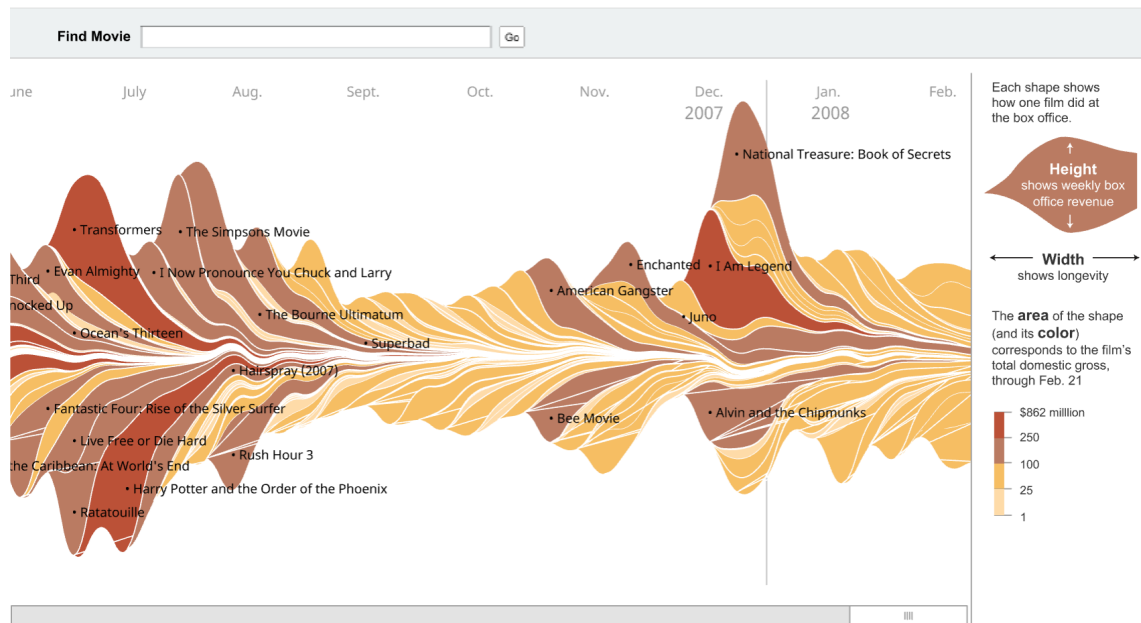
Representing multidimensional data in a two-dimensional visual display is not a trivial task. The process requires analytical and visual/spatial methods of reasoning. According to Meirelles [2013] visualizations can serve multiple purposes, such as a means to communicate, whether it is to narrate stories, present research findings, or provide platforms for interactive data manipulation and exploration. When viewed as cognitive artifacts, visualizations align with principles that enhance cognitive processing, which includes the following capabilities [Meirelles, 2013]:

February 23, 2008

FEEDBACK

The Ebb and Flow of Movies: Box Office Receipts 1986 — 2008

Summer blockbusters and holiday hits make up the bulk of box office revenue each year, while contenders for the Oscars tend to attract smaller audiences that build over time. Here's a look at how movies have fared at the box office, after adjusting for inflation.



Sources: Baseline StudioSystems; Box Office Mojo

Mathew Bloch, Lee Byron, Shan Carter and Amanda Cox

Figure 3.2: Visualization of The Ebb and Flow of Movies: Box Office Receipts 1986 — 2008 (adapted from [Mathew Bloch and Cox, 2008])

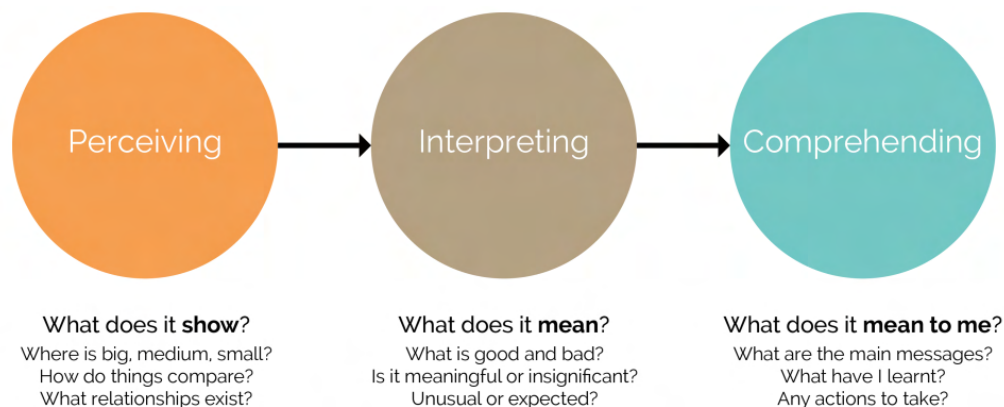


Figure 3.3: The Three Phases of Understanding (adapted from [Kirk, 2019])

- Record information;
- Convey meaning;
- Increase working memory;
- Facilitate search;
- Facilitate discovery;
- Support perceptual inference;

- Enhance detection and recognition;
- Provide models of actual data and theoretical worlds;
- Provide manipulation of data.

3.1.1 Data Visualization Process and Pipeline

The data visualization process is usually represented as a pipeline that is made of sequential stages. One of the first to propose a pipeline for visualizations was Card et al. [1999] this pipeline can be seen as a conceptual model to describe how to transform raw data into a visual output. Figure 3.4 illustrates a generalized pipeline.

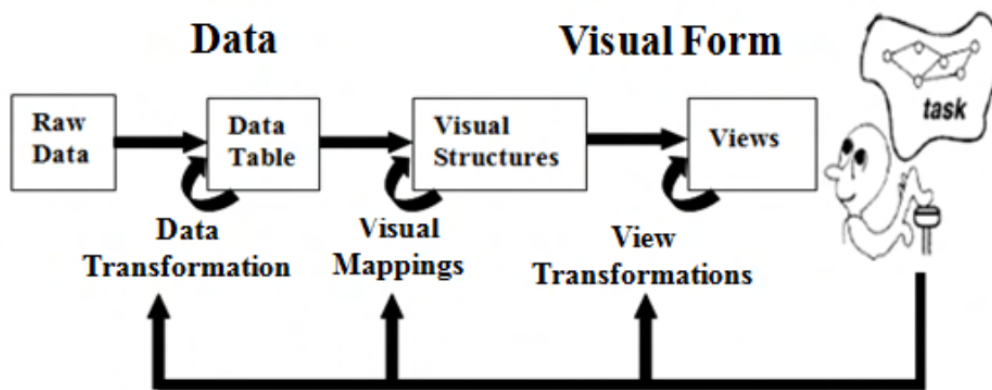


Figure 3.4: Reference model for visualization (adapted from [Card et al., 1999])

This pipeline shows a systematic flow from raw data to visualization, taking into consideration user input, or as it's represented, the user task and it assumes a linear process. This model captures the creation of the visualization but not the user experience or it's perception, it may describe how to create a visualization but does not consider the environment where the visualization can be best presented and the user interactions, being referred just as user tasks.

Data, Transformations, and Tables

Raw data can be found in many formats, like text files, Comma Separated Values (CSV), Extensive Markup Language (XML), databases, and be from one or more data sources. Usually, this data has errors, null values, and omitted values and is hardly clean and ready to use, meaning it needs to be processed to be prepared for use. The role of data transformations is to process raw data into a form that can be suitable for visualization, data transformations can include:

- Extract data;
- Filter data;

- Clear data;
- Transform data into a suitable format for analysis.

The data table represents a data structure, usually in rows and columns. Each row represents a dimension or a variable with metadata encoding, for example, the names, types, dates, positions, etc. Each line represents an item. The data type is essential to choose a visualization technique to represent it better. Once a method is chosen, many parameters are determined from them, such as the Mapping.

Data Mapping

From a data table, raw data is transformed into visual marks. The next steps are to define how the data will be visually decoded and how to present them in a spatial organization. The first to describe visual variables was [Bertin, 1983], he classified them as selective, associative, quantitative, and of order. Most of the visual structures used to form visualizations are visible marks like dots, lines, areas, volumes. Then, graphical attributes are introduced, such as position, shape, size, form, orientation, color, and texture (Figure 3.5). Note that the figure summarizes visual variables and their levels of perception, it does not cover the full scope of graphical semiology, which extends beyond visual mapping.

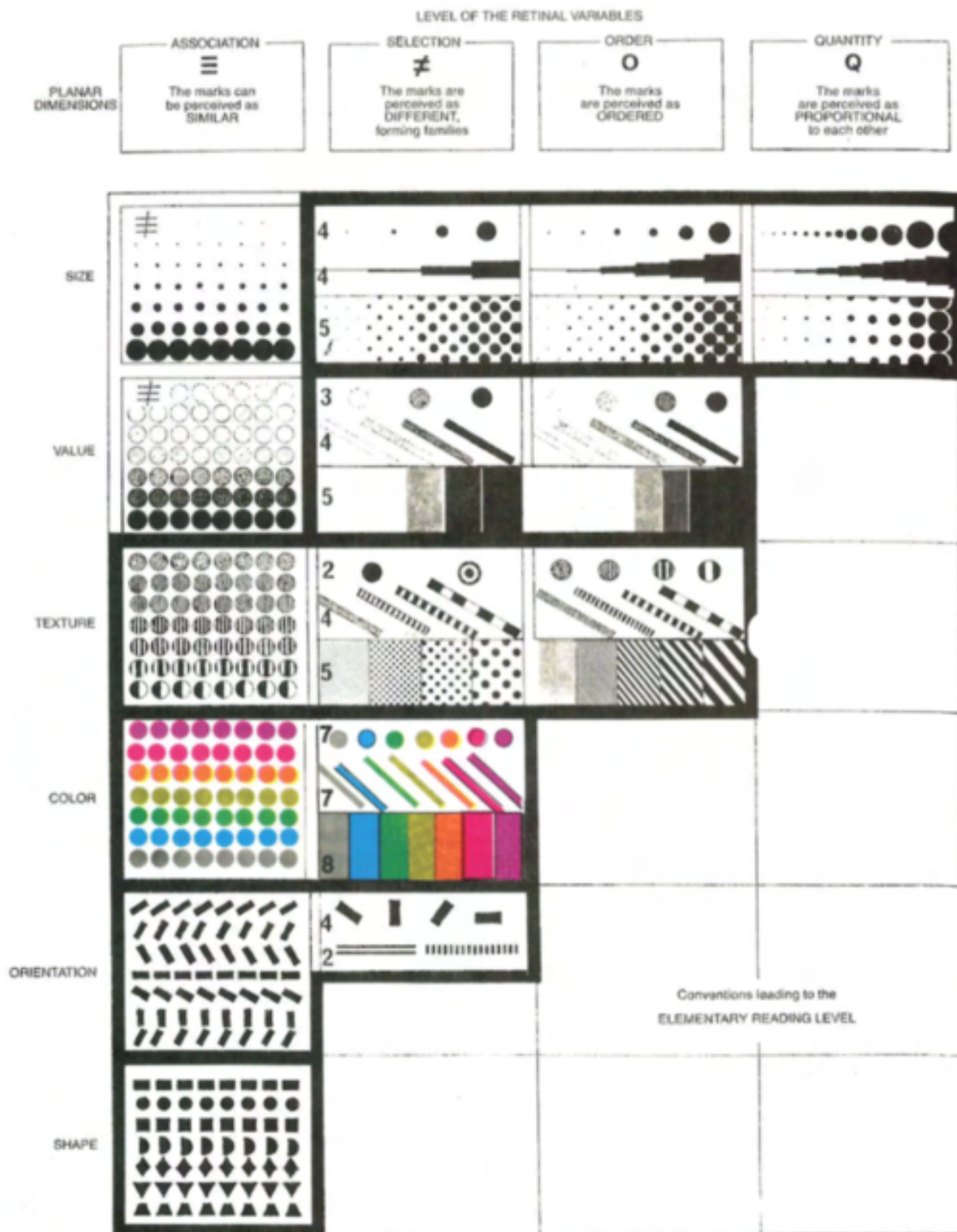


Figure 3.5: The table of visual variables and their level of perception according to Bertin (adapted from [Bertin, 1983])

Numerous taxonomies have been proposed to organize visualization techniques according to the type of data, being unidimensional, bidimensional, tridimensional, multidimensional, temporal, hierarchical, and network. Taxonomy denotes the classification scheme that groups techniques by data structure, the techniques are the items being classified.

Visualization techniques are the concrete graphical methods used to encode data

into marks and visual variables (Figure 3.6).

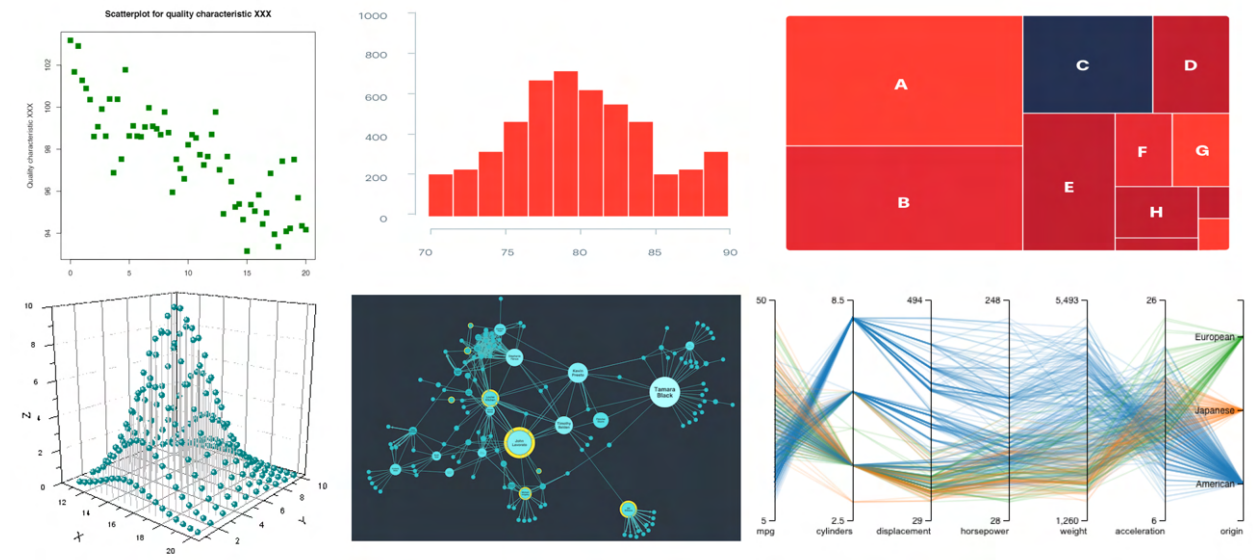


Figure 3.6: Visualization techniques from left to right: scatter plot (bidimensional), histogram (unidimensional), treemap (hierarchical), 3D surface/mesh (tridimensional), node-link diagram (network), parallel coordinates (multidimensional).

Views and View Transformation

This stage refers to the act of refining and interacting with the data. View transformation is where users interact and manipulate the data. With technological advancements and computational visualizations, new forms of interactions have become possible with digital visualizations. To better analyze the data and extract meaningful information, according to [Saket et al., 2018], some of the essential tasks for an analysis are:

- Find Anomalies: Find abnormal data points that deviate from most values;
- Find Clusters: Find groups of data with similar attribute values;
- Find Correlations: Find if two or more data attributes are correlated;
- Compute Derived Value: Calculate a summary or aggregate values from a set of data;
- Characterize Distributions: Identify how an attribute's values are distributed over the dataset;
- Find Extremes: Locate data points with the maximum or minimum values for an attribute;
- Filtering: Find data points that satisfy specific conditions;
- Order: Sort data based on specific metrics;

- Determine Range: Identify the span of values for a particular attribute;
- Retrieve Value: Look up specific attribute values for given data points.

[Saket et al., 2018] also established a relation between these tasks and performance metrics based on the time and user preference using different graphics, in Figure 3.7 we can see that the efficiency of performing some tasks varies depending on the visualization used.

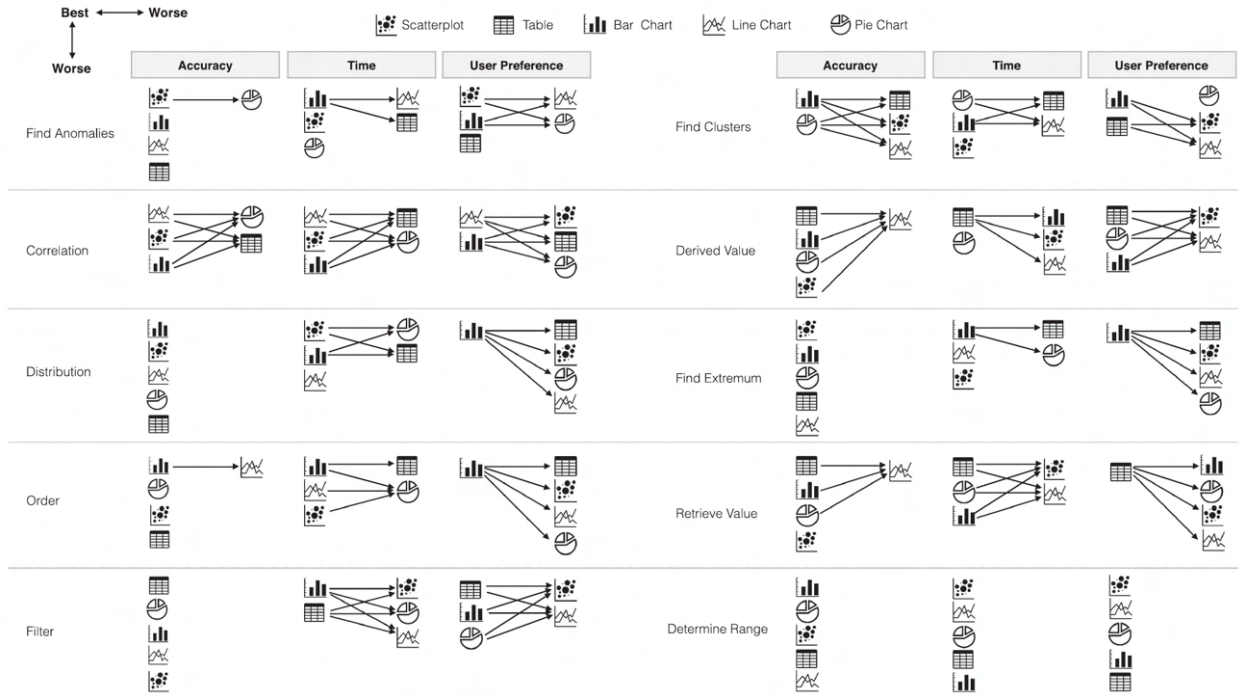


Figure 3.7: Efficiency performance metrics (adapted from [Saket et al., 2018])

3.1.2 Principles of Data Visualization

As discussed previously, visualization can be a cognitive bridge that links abstract data to our perceptual and conceptual understanding [Card et al., 1999]. The principles used in data visualization are mainly visual design guidelines and interactivity best practices that were refined over years of practice and evaluation. While these principles are not rigid rules, they do provide a framework that can help guide design decisions and make sure that visual representations are comprehensible. Some of these principles, such as the fundamental concepts of visual encodings, semiology, and the data visualization pipeline, were discussed in the previous section, so in this section, the focus will be on a broader set of principles that also guide effective visualizations.

Audience

A good visualization needs to align the knowledge, interests, and goals of the intended audience. Different user groups have different levels of expertise, time constraints, and needs [Kirk, 2019; Meirelles, 2013]. A visualization designed for specialists in a specific field may incorporate vocabulary not suitable for a more general audience, things like complex metrics and advanced filtering tools can be useful for one public but not the other. A more general audience usually requires more straightforward explanations, simple encodings, and avoidance of domain-specific vocabulary.

Clarity

One of the main goals of data visualization is to make sure the information presented is clear. Clarity ensures that viewers can quickly understand what is being shown, besides choosing the correct visual encodings, clarity also involves adequate labeling, mindful selection of the chart and its elements, and maintaining appropriate scales and baselines [Meirelles, 2013; Ware, 2019].

Minimizing visual elements that do not have a purpose in the visualization is a must, making sure that every component works to emphasize understanding. This principle is also very related to the target audience. Overly complicated charts may be helpful for some audiences while not suited for others that are not experts in certain fields, an excess of interaction mechanisms can also overwhelm viewers.

Contextualization

Data never exists alone. Good visualizations provide context that helps viewers identify patterns. This can include annotations, labels, and explanatory text to help the user's interpretation without overshadowing the data [Kirk, 2019].

Highlighting specific points of interest, trends, outliers, etc. By doing this, the

visualization can tell a story or show insights that could remain hidden if the viewer is forced to guess the importance of certain patterns. When done well, annotations can help viewers understand and also let them explore and find more patterns on their own. According to [Kirk, 2019], by using a good frame, the visualization becomes not just an image but a way to better understand the patterns in the data.

Graphical Integrity

Visual representations of data must tell the truth. When viewers rely on data visualizations to make decisions, draw conclusions, or form opinions, any visual distortion can mislead and create false narratives. Being mindful to how scales, proportions, and baselines are chosen, as well as how visual elements correspond to the values they are depicting.

According to Tufte's principles of graphical excellence and integrity [Tufte, 1985], each graphical element, being a bar, line, area, or symbol, should be directly proportional to the magnitude of the data it's representing. A proportional relationship let viewers compare elements without having to think too much about it.

Improper use of scales, can exaggerate differences between data points, passing the impression of dramatic changes where the real variations may be more subtle. Ensuring accurate baselines and using appropriate scaling methods, like logarithmic scales can help maintain an honest representation.

Tufte also introduced the concept of the "Lie Factor" to quantify the extent to which a representation deviates from the actual data. The Lie Factor is defined as the ratio of the size of an effect shown in the graphic to the size of the effect in the data.

$$\text{Lie Factor} = \frac{\text{Size of the effect shown in the visualization}}{\text{Size of the effect in the data}}$$

A Lie Factor near 1 indicate an accurate representation, values significantly greater or less than 1 suggest some kind of distortion, being it overstating the effect if it's greater than 1.05 or understate the effect if lower than 0.95.

Data-Ink Ratio

Another principle introduced by Tufte is the concept of the data-ink ratio [Tufte, 1985]. Every mark on the page or screen should serve a purpose. The data-ink ratio means the proportion of a graphic that cannot be erased without losing information, he says that good representations maximize data-ink and erase as much non-data-ink as possible. In practice, this can be achieved by removing any ornamental elements, often referred to as "chartjunk", that do not add explanatory value.

Data Density

Data density is how much of the picture, or frame, is used to show data. A high-density visualization can show complex structures, making it easier to compare charts without switching between many charts. But a large amount of data density need to be done carefully, having a single chart with too many data points, lines, categories can compromise clarity. The space should be optimized to reveal as much meaningful information as possible without sacrificing readability.

3.2 Data Physicalization

According to Jansen et al. [2015], data physicalization is a field that aims to investigate how physical objects can codify data through their physical and visual characteristics using different geometries and materials. Just like information visualization, data physicalization transforms abstract information into physical artifacts to support cognition, communication, learning, problem-solving, and decision-making. While information visualization mainly relies on visual channels, data physicalization uses physical objects to represent data, making it possible to touch, see, or interact with the data through the object's shape, materials, and other physical features. [Chiang, 2018; Dragicevic et al., 2019; Jansen et al., 2015].

The previous section talked about concepts related to information visualization, including how visual encodings are chosen to represent data attributes. Data physicalization also have these considerations, but places a stronger emphasis on the tactile and spatial dimensions of representation. It overlaps with fields like human-computer interaction (HCI) and tangible user interfaces (TUIs), which study how physical artifacts can be both input and output devices for computational systems [Ishii, 1997; Ullmer and Ishii, 2000]. It also applies to the field of product design, where form, material, and functionality are used to create meaningful user experiences.

Historical Context

The idea of using physical representations to encode data is nothing new. Way before computers existed, humans used physical artifacts to record, communicate, and manipulate information. One of the oldest artifacts found was the Ishango bone (approximately 22,000 BC), having a sequence of marks carved in small groups (Figure 3.8) that were interpreted as tally marks (a way to mark or record counting). In David Darling's online encyclopedia, he speculates the artifact could have been

"Used as a lunar phase counter, in which case African women may have been the first mathematicians, because keeping track of menstrual cycles requires a lunar calendar"

[Darling].



Figure 3.8: Ishango bone (22,000 BC)

Other artifacts, such as the clay tokens (around 4,000 BC), were present in Mesopotamia (Figure 3.9), being used as a counting system [Schmandt-Besserat, 2010]. Different shapes of tokens represented different representing specific farming goods (grain, sheep, goat, etc) and their amount encoded quantities.

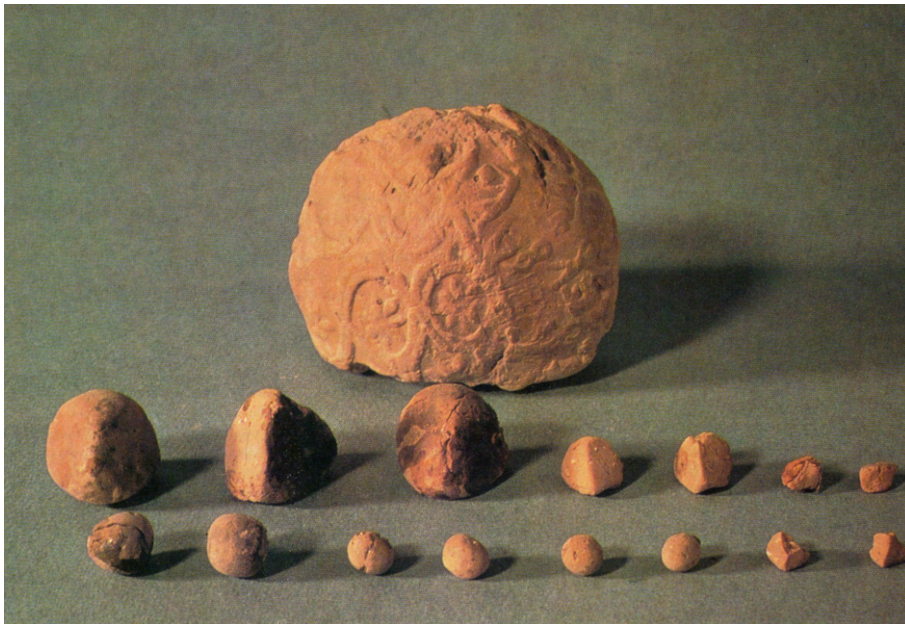


Figure 3.9: Mesopotamian clay tokens (4,000 BC)

Discovered in a shipwreck off the Greek island of Antikythera, the Antikythera Mechanism (150 BC) is considered the earliest known analog computer (Figure 3.10) [de Solla Price, 1974; Freeth et al., 2006]. This device consisted of a complex system of precision bronze gears, its mechanism physically encoded mathematical models of celestial motions, transforming abstract data into a mechanical form that could be manipulated by hand. By turning a handle, it was possible to simulate the motions of the Sun, Moon, planets and predict eclipses and other celestial events.

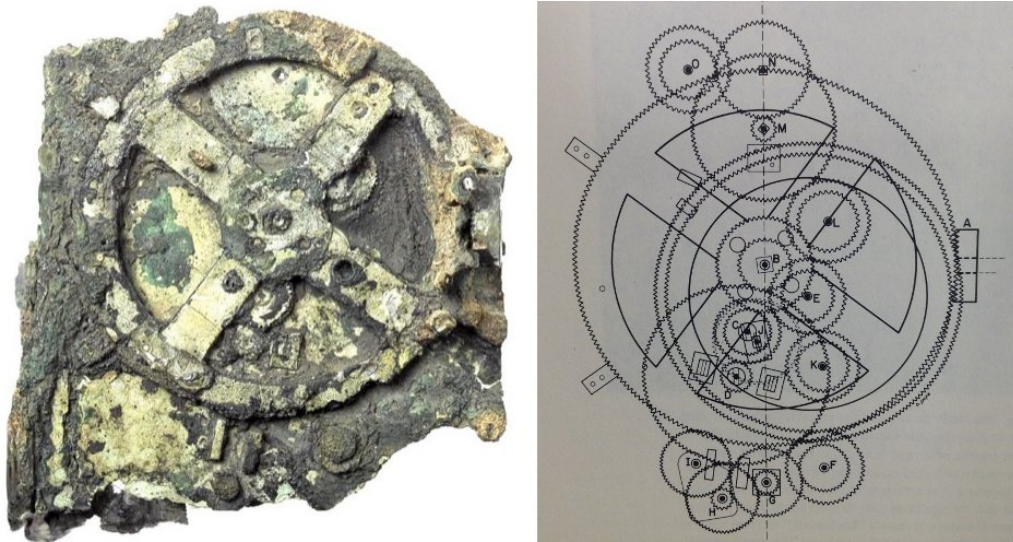


Figure 3.10: Left: Fragment A of the Antikythera Mechanism. Right: Diagram of the gearing of the Antikythera Mechanism [TheAthensKey, 2005]

The astrolabe (150 BC) is also an astronomical instrument that was used to measure the time and heights of stars (Figure 3.11). Originating in the Hellenistic civilization and improved by Islamic astronomers [North, 1974], the astrolabe is basically a two-dimensional model of the celestial sphere, encoding data like the star positions, the Sun's path, having a stereographic projection of the celestial sphere. features are an analog encoding of data about celestial objects, transforming abstract astronomical calculations into mechanical manipulations. Astrolabes parallel more modern data visualizations that support exploratory tasks.

As paper and printing technologies emerged and became more accessible to the general public, the practice of physically representing data continued. For example, in the 19th and early 20th century, some engineers and planners built models to visualize metrics like energy consumption (Figure 3.12) [Brinton, 1919]. These physicalizations served more pragmatic and analytical purposes, similar to data visualizations on screens, but in a tactile and tangible form.



Figure 3.11: Medieval astrolabe

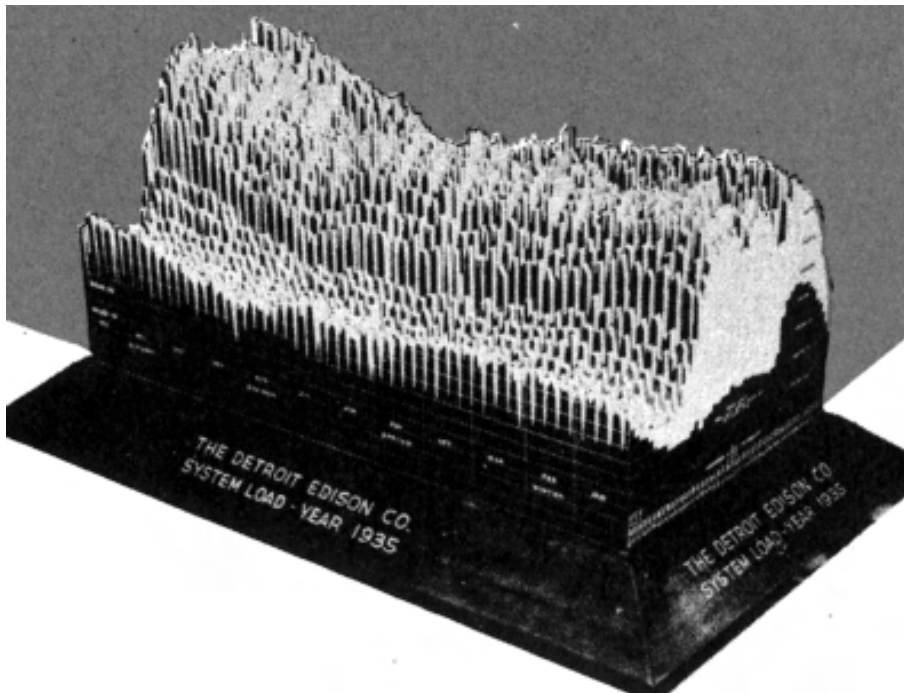


Figure 3.12: Power consumption visualization from Detroit Edison Company

Classification

The literature has some terms to categorize different types of data physicalizations. Some initial classifications focused more on whether a physicalization was static, dynamic, or if the integrated artifact used some computational feedback.

Over time, more factors started to be considered, like the artifact's purpose, user interaction, sensory modalities, and how the representation is used within the environment or user context [DataPhys]. This classification is not definitive for one type of physicalization since multiple classifications can apply to a single representation.

- **Static (Passive) Physicalizations:**

Static physicalizations present data in a stable form, often referred to as data sculptures or data art (Figure 3.13), they can be produced with digital fabrication techniques (3D printing, laser cutting) or handcrafted methods. They require no electronic components, and their form does not change over time. They encode data by shape, size, texture, and material composition. [Dragicevic et al., 2020].



Figure 3.13: Global Cities: Elevation Maps of City Population [Williams, 2007]

- **Dynamic (Active) Physicalizations:**

Dynamic physicalizations can change form, shape, or other physical characteristics in response to updates from the dataset (Figure 3.14). They can incorporate electronic components to change their physical form [Willett et al., 2016]. These physicalizations can be driven by real-time data, but they don't necessarily respond to user interaction.

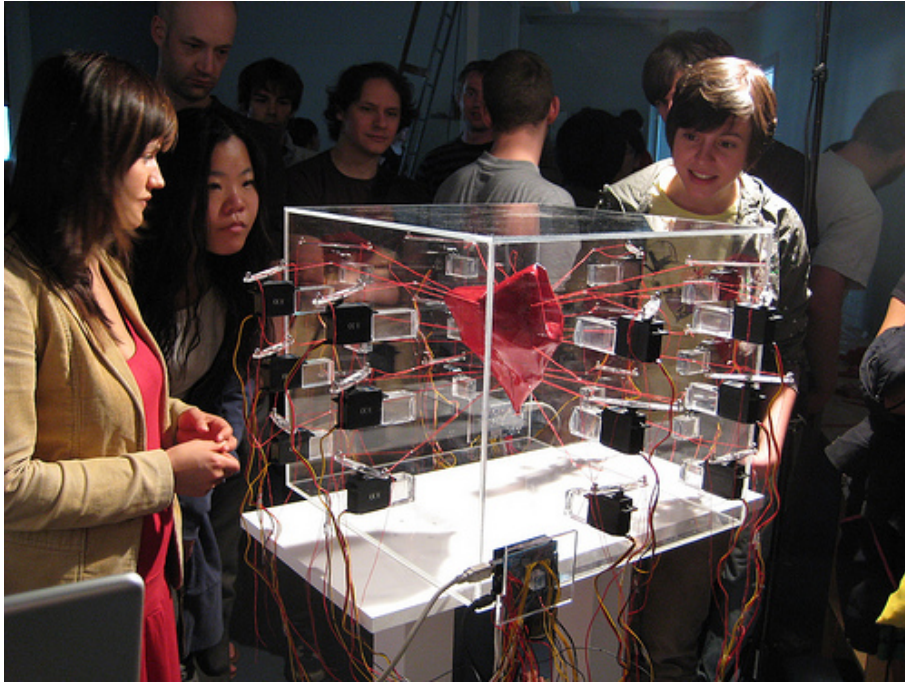


Figure 3.14: Pulse: Animated Heart Shows Sentiments [Kison, 2009]

- **Augmented or Hybrid Data Representations:**

Some physicalizations integrate both physical and digital elements, it's very common to use augmented reality on those, where the physical object serves as the basis for the representation and can be digitally complemented with projections (Figure 3.15), overlays of augmented reality, or lighting, showing additional dimensions that allow users to explore more of the data. [Dragicevic et al., 2020].



Figure 3.15: Emoto data sculpture showing Twitter sentiments during the Olympic games 2012 [Moritz Stefaner and NAND, 2012]

- **Rearrangeable or Modular Physicalizations:**

Some physicalizations can consist of multiple components that can be manually or automatically rearranged to represent different subsets or perspec-

tives of the data, encouraging exploration (Figure 3.16) even if the physicalization is not automated or actuated. These physicalizations allow dynamic re-mapping of data without rebuilding the entire artifact Willett et al. [2016].



Figure 3.16: Let's play with data by Jose Duarte[Huron et al., 2022]

- **Contextualized Physicalizations:**

Contextualized physicalizations represent data in the environment where it is obtained (Figure 3.17). Having data in its original context can help understanding and interpretation, making the representation more relevant and intuitive. This approach becomes more direct and meaningful, turning that environment a place-specific narrative [Regan et al., 2015]



Figure 3.17: Tenison Road Charts [Richard Banks, 2014]

- **Interactive Physicalizations:**

Interactive physicalizations allow the user to directly manipulate the data through physical actions [Jansen et al., 2015] (Figure 3.18). This interaction can be achieved with electronic components, digital fabrication mechanisms, crafted mechanisms, etc. Some interactions can blur the line between tangible user interfaces (TUIs) and data visualizations. [Ijeoma, 2022; Le Goc et al., 2018].



Figure 3.18: Wage Islands by Ekene Ijeoma [Huron et al., 2022]

- **Incorporated and Embedded Physicalizations:**

Incorporated physicalizations are bound to the object, the data can drive the shape, material, or structural properties, the object form is inseparable from the information it represents (Figure 3.19), creating objects associated spatially and semantically with their data source [Le Goc et al., 2018].

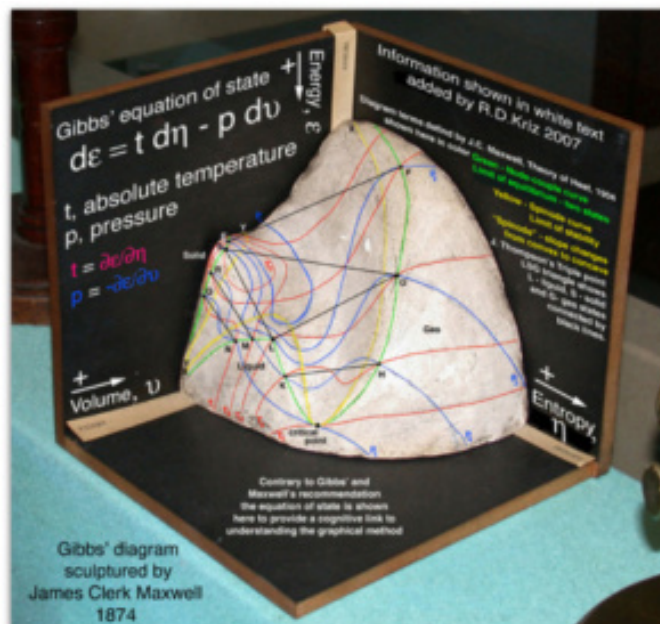


Figure 3.19: Maxwell's Thermodynamic Surface. [Maxwel, 1875]

- **Personal Physicalizations:**

These are physical representations of personal data, allowing people to turn their own data into tangible forms to track and reflect on it [Borghoff et al., 2000].



Figure 3.20: LOOP: Ambient Visualization of Personal Activity [Huron et al., 2022]

3.2.1 Data Physicalization Pipeline

Just as information visualization, data physicalization also has a reference model to describe how information becomes encoded into physical forms. The fundamental idea is to expand the classic "information visualization pipeline" (Figure 3.4). Jansen and Dragicevic [2013] proposed an extended pipeline model (Figure 3.21) specifically for data physicalization. This model describes how abstract data can be transformed into a physical artifact and also integrates user perception, interpretation, and interaction with the physical form.

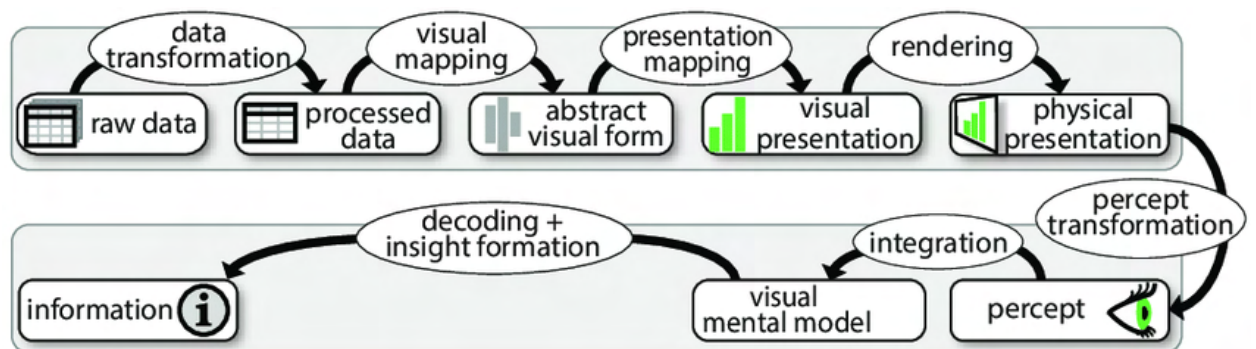


Figure 3.21: Physicalization Pipeline [Jansen and Dragicevic, 2013]

It starts from the same foundations as traditional information visualization. Beginning with raw data that must be cleaned, transformed, and mapped into visual variables. However, the pipeline extends beyond the digital screen. After the visual design is set, the chosen representation is "rendered" into a physical artifact. The final artifact can be static or dynamic, handcrafted or machine-fabricated, it materializes the data into a tangible form. The user then perceives, interprets, and interacts with this artifact.

Some of the processes, such as raw data and data transformation, were already discussed in the Information Visualization Pipeline section, so here, the focus will

be on the processes that were not mentioned in this expanded version.

Visual Mapping:

Once the data is processed, it needs to be associated with visual variables such as size, shape, height, color, and texture. The conceptual step is similar to a standard information visualization approach, but with the data being physical, the mapping must consider the fabrication constraints and the intended use of the final artifact.

Presentation Mapping:

After choosing a visual encoding, the data must be translated into instructions for a physical fabrication process. This can include the geometry in a 3D model, selecting materials, and determining fabrication parameters. This stage includes decisions about the materials, colors, finishing techniques, and labels used in the artifact.

Rendering:

Once the presentation is defined, the pipeline enters the rendering phase, where the data will be transformed into a physical artifact. Rendering in data physicalization is a broader concept than rendering a digital image. It takes into consideration the entire fabrication process that results in a tangible object, it can be fully digital, using 3D printers, laser cutters, CNC machines, or it can be fully manual involving artisanal craftsmanship, clay modeling, or using building blocks [Huron et al., 2014]. Material also plays an important role in this stage since the choice of material can convey meaning or influence interpretation [Jansen et al., 2015]

Physical Presentation

Once the artifact is constructed and occupies space in the real world, we enter the physical presentation stage. The physicalization now exists as a tangible object in a particular environment. The placement, lighting, and context can influence how it will be perceived, the environment can become part of the interpretation, guiding how people read the data [Hornecker and Buur, 2006].

Perception

Human perception is multimodal. Vision still plays a crucial role, but haptics (touch), proprioception (spatial awareness of one's own body), and even auditory cues can come into play. As Jansen et al. [2015] discuss, the physical world's constraints and affordances shape how users interpret and understand data. A

user might walk around a physicalization to view it from different angles, bend to inspect details, or pick it up to examine the other sides, which is more limited to do on a flat screen. While perception in 2D visualization relies predominantly on vision, data physicalization uses more sensory modalities, [Hornecker and Buur, 2006] described the types of variables that can be codified in a physicalization: (Table 3.1)

Table 3.1: **Variable Types and Options** adapted from [Hornecker and Buur, 2006]

Variable Type	Options
Physical variables	density, electrical resistance, hardness/compliance, permeability, pyrotechnic colour, reflectance, slipperiness, smoothness, sponginess, stiffness, tensile strength, thermal diffusivity, thermal expansion, viscosity, weight, material visual location, colour hue, colour value, colour saturation, visual size
Visual variables	visual location, colour hue, colour value, colour saturation, visual size, visual shape, visual orientation, visual arrangement, visual texture, crispness, resolution, visual numerousness
Haptic variables	vibration amplitude, vibration frequency, pressure/force–strength, temperature, resistance, friction, kinesthetic location, tangible size, tangible elevation, tangible shape, tangible texture, tangible orientation, tangible location, tangible arrangement, tangible numerousness
Sonic variables	sound source location, loudness, pitch, register, timbre, attack/decay, rhythmic patterns
Olfactory variables	scent type, scent direction, scent saturation, airflow rate, air quality
Gustatory variables	taste type, temperature of the taste carrier
Dynamic variables	perception time, temporal order, duration, temporal frequency, rate of change, synchronization, change pattern

Physical Variables

- **Density:** Reflects how compact or “heavy” a material feels for its size.
- **Electrical Resistance:** Indicates how easily current flows through a material. This could be changed by substituting conductive vs. insulating materials.
- **Hardness/Compliance:** Describes a material’s rigidity or flexibility.
- **Permeability:** Relates to how easily a fluid passes through.
- **Pyrotechnic Colour:** Involves color changes triggered by heat or combustion effects.

- **Reflectance:** Defines how much light bounces off a surface.
- **Slipperiness:** Conveys friction levels.
- **Smoothness:** Reflects surface texture.
- **Sponginess:** Denotes how compressible or cushiony an object is.
- **Stiffness:** Closely related to hardness but focused more on structural rigidity.
- **Tensile Strength:** Measures a material's ability to resist pulling forces.
- **Thermal Diffusivity:** Reveals how rapidly an object adjusts to temperature changes.
- **Thermal Expansion:** Captures how much a material's dimensions change with temperature.
- **Viscosity:** Relevant for fluid or semi-fluid materials.
- **Weight:** Simply how heavy an object is.
- **Material Visual Location:** Where and how the material is positioned within the overall design.
- **Colour Hue, Value, Saturation, Visual Size:** Although often considered "visual" attributes, they're listed here to emphasize that color and size can be intrinsic to a material rather than just surface finishes.

Visual Variables

- **Visual Location:** The position of elements in space or within a layout.
- **Colour (Hue, Value, Saturation):** The core components defining a color's type, lightness/darkness, and intensity.
- **Visual Size:** The scale or dimension an element occupies visually.
- **Visual Shape:** The outline or contour that defines an object's form.
- **Visual Orientation:** The angle or rotational aspect of an object.
- **Visual Arrangement:** How elements are grouped or structured relative to each other.
- **Visual Texture:** The appearance of a surface's pattern or fineness.
- **Crispness, Resolution:** The level of clarity or detail in an element.
- **Visual Numerousness:** The count or density of repeated visual elements.

Haptic Variables

- **Vibration Amplitude/Frequency:** The intensity and rate of oscillatory motion.
- **Pressure/Force–Strength:** The degree of force applied or experienced upon contact.
- **Temperature:** The perceived warmth or coolness of a surface.
- **Resistance, Friction:** The opposition to motion or sliding contact.
- **Kinesthetic Location:** Where on the body (or in space) a user perceives a physical movement or force.

Sonic Variables

- **Sound Source Location:** The perceived origin of a sound in space.
- **Loudness:** The volume or intensity of the sound.
- **Pitch, Register:** How high or low a tone is, or its general range.
- **Timbre:** The characteristic “color” or quality that distinguishes different sounds.
- **Attack/Decay, Rhythmic Patterns:** How quickly a sound starts or fades, and the recurring beats or pulses it forms.

Olfactory Variables

- **Scent Type:** The qualitative smell category
- **Scent Direction, Saturation:** The spread of a smell through space and its intensity or concentration.
- **Airflow Rate, Air Quality:** Conditions that carry scent, influencing how it diffuses or how clean/tainted it appears.

Gustatory Variables

- **Taste Type:** The fundamental flavor (sweet, salty, sour, bitter).
- **Temperature of the Taste Carrier:** The warmth or coolness associated with the edible medium.

Dynamic Variables

- **Perception Time, Temporal Order, Duration, Temporal Frequency:** The sequencing and pacing of changes or events.
- **Rate of Change, Synchronization, Change Pattern:** How quickly something transforms, the coordination among multiple elements, and the recurring style or structure of modifications.

Integration and Visual Mental Model

When there is any engagement with the physical artifact, the public forms a mental model of the data, this model evolves as they interact with it. Just like data visualization, perception is considered a cognitive process, and by exploring a physicalization, users can modify the previously conceived mental model. The tangible nature of the artifact can also encourage collaborative interpretation, where many users talk about what they see and feel, refining their own mental models [Hornecker and Buur, 2006].

Decoding and Insight

Decoding translates what is seen in the visualization back into the data values. This means recognizing which visual encodings or mappings are used and then retrieving the original numbers or categories they represent. The difficulty of decoding depends mainly on how familiar and visually literate the viewer is and how the chosen encodings correspond to the data. When users see trends or differences in the data, the process goes from decoding to insight. Insights appear when information is put together and explained in context.

3.2.2 Digital Fabrication

Digital fabrication technologies have reduced some barriers to producing physical data representations, enabling faster prototyping and the creation of more complex static physicalizations [Le Goc et al., 2018]. Nevertheless, some challenges are still present, such as adapting data representations to suitable scales and dimensions, designing a stable physical assembly, and making sure the results are interpretable [Djavaherpour et al., 2021]. Digital fabrication has many manufacturing approaches, each offering different possibilities for data physicalization:

- **Cutting:**
Laser cutting, waterjet cutting, or slicing through flat sheets of material to produce 2D shapes are efficient methods for creating simple, layered encoding artifacts, like maps, grids, or stacked structures.
- **Subtractive:**
These are techniques that remove material from a solid block until the desired shape emerges. CNC milling, for example, can be used for this purpose.
- **Additive:**
This technique builds objects by adding layers of material; a common tool known for this is 3D printing, which incrementally builds objects. These processes are great to produce complex geometries and internal structures that might be challenging or impossible to achieve with other methods.

- **Formative:**
Methods that use external forces such as heat or steam to reshape existing materials into new configurations.
- **Hybrid:**
These methods combine multiple fabrication methods, such as integrating CNC-milled components with laser-cut parts or 3D-printed elements to create a more intricate physicalization.

3.3 Data Visualization in Awareness Campaigns

Information visualization has the potential to not only communicate complex data but also influence public perception and shape discourse [Sheppard, 2005]. While information visualization is frequently used in analytical settings, there are also many uses in awareness and mitigation campaigns. Awareness campaigns usually aim to bring attention to problems frequently invisible, neglected, or misunderstood by the general public. Some common subjects can be pollution, environmental degradation, health crises, social inequities, human rights abuses, among others. Unlike marketing campaigns, which often promote a product or service, awareness campaigns can advocate for policy changes, individual behavior modifications, or public dialogues about pressing issues [Krum, 2013]. While this section emphasizes more two-dimensional and digital visualizations, the field of data physicalization [Dragicevic et al., 2019; Jansen et al., 2015] also offers parallel possibilities for tangible experiences.

3.3.1 Case Studies

U.S. Gun Deaths by Periscopic

The interactive visualization "U.S. Gun Deaths" by Periscopic [Periscopic, 2013] (Figure 3.22), addresses the gun violence problems in the United States. This project stands out for the combination of emotional storytelling and data-driven accuracy.



Figure 3.22: Gun Deaths by Periscope [Periscope, 2013]

The visualization provide a clear and emotionally engaging portrayal of gun-related fatalities across the United States. Using data from the Centers for Disease Control and Prevention (CDC) and the Federal Bureau of Investigation (FBI), the visualization shows the victim's age, gender, and location. The data is then connected to a projection of how many years of life were lost, had those individuals lived a full life expectancy. It is also possible to see more details, such as the victim's age, gender, and cause of death (homicide, suicide, accident, etc).

What sets Periscope's project apart is how it presents the data, instead of just stating statistics, the visualization reveals the individual magnitude of each loss. Transforming the numbers into compelling narratives [Tufte, 1985] and showing the weight of the problem. This project received a lot of attention and was featured in high-profile media outlets. Advocacy groups citPeriscope'slization in discussions about gun control policy, and it sparked social media conversations nationwide [Periscope, 2013].

#MeToo Momentum

The "#MeToo Momentum" (Figure 3.23) platform aggregates tweets, news stories, and personal blog entries referencing the #MeToo hashtag. The data includes:

- Geographical locations of tweets;
- The frequency of mentions over time;
- Feeling analyses (expressions of anger, solidarity, or shock).

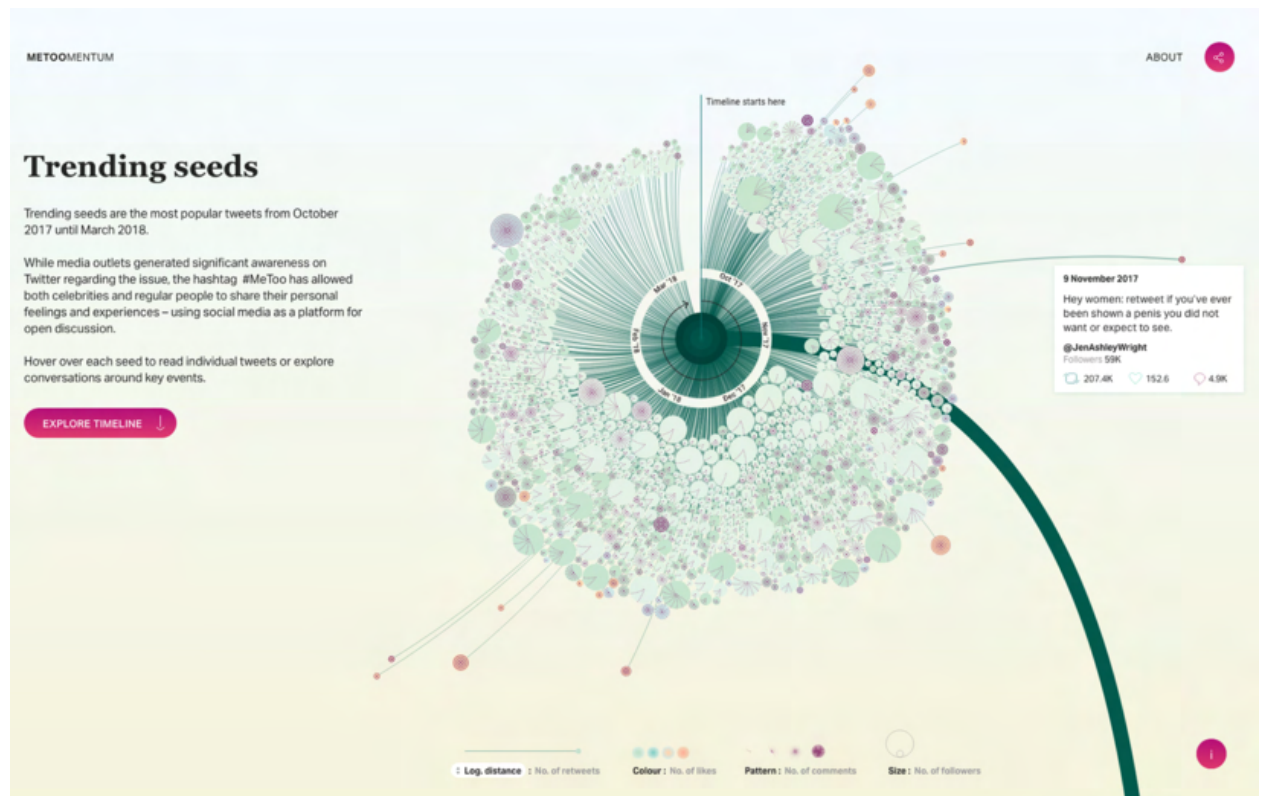


Figure 3.23: #MeToo Momentum [D'Efilippo, 2019]

The platform depicts how fast the movement spread and where clusters of discussions were emerging. It was possible to filter the data by region, time, and even language, which created a personalizable experience.

Some media outlets talked about the platform's statistics in articles covering the movement, and activists used visual snapshots in campaigns calling for workplace policy reforms [D'Efilippo, 2019]. The visualization functioned as a record of digital activism and a tool for advocacy, persuasion, and solidarity.

Climate-Conflict.org: Mapping Climatviewers' and Violence

This platform seeks insights into the link between climate change and conflicts, where scarcity of resources or extreme weather may exacerbate tensions in already fragile regions. The platform "Climate-Conflict.org: Mapping Climatviewers' and Violence" [TruthandBeauty, 2022] uses data visualization to draw attention to these relationships.

The site collects data from institutions such as the United Nations Environment Programme (UNEP), the Arme's Conflict Location & Event Data Project (ACLED), and other databases focusing on environmental changes. It tries to provide global coverage, focusing on hotspots where climate stress and sociopolitical instability converge.

The platform uses a combination of Geospatial Mapping, indicating the severity of climatic events overlaid with conflict events like protests or armed clashes

(Figure 3.24). It also uses side-by-side bar charts or lines illustrating declines and rises in local conflicts.

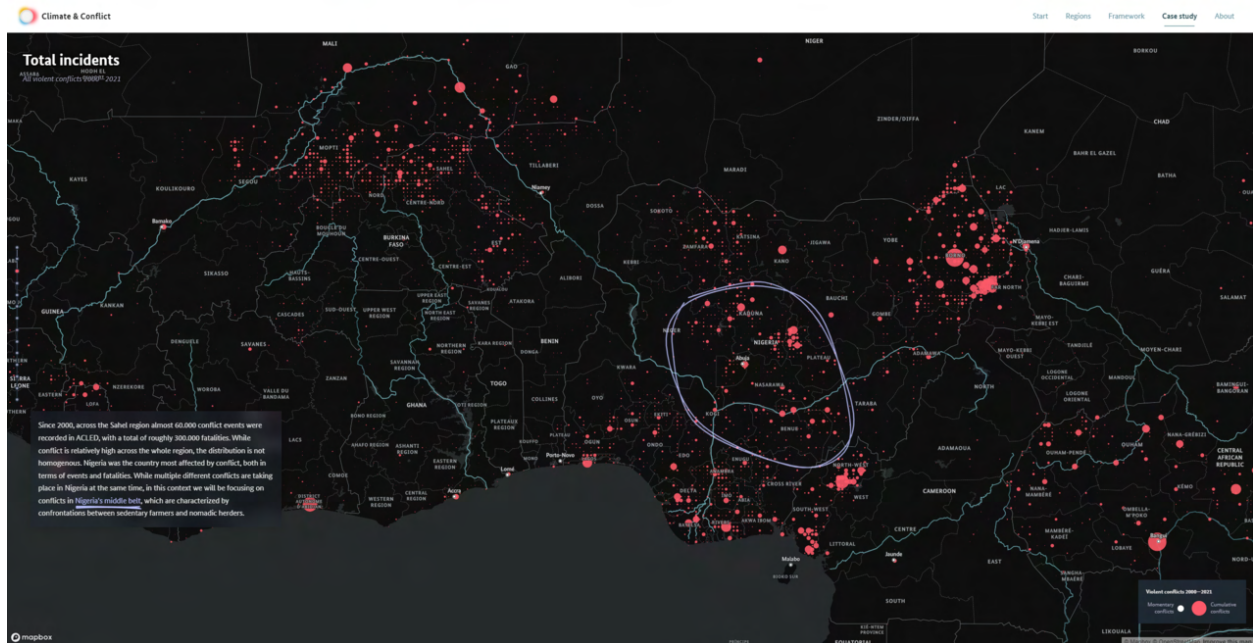


Figure 3.24: Climate-Conflict.org [TruthandBeauty, 2022]

Infographics in Context by Peter Ørntoft

Fitting more into a physicalization than a data visualization, Infographics in Context (Figure 3.25) connects the data with a physical and contextual setting [Ørntoft, 2011]. The authors puts statistical data about Danish public opinion directly into photographs featuring real people and symbolic objects, each infographic is arranged in a real-life scene or paired with physical material that reinforces the subject matter.

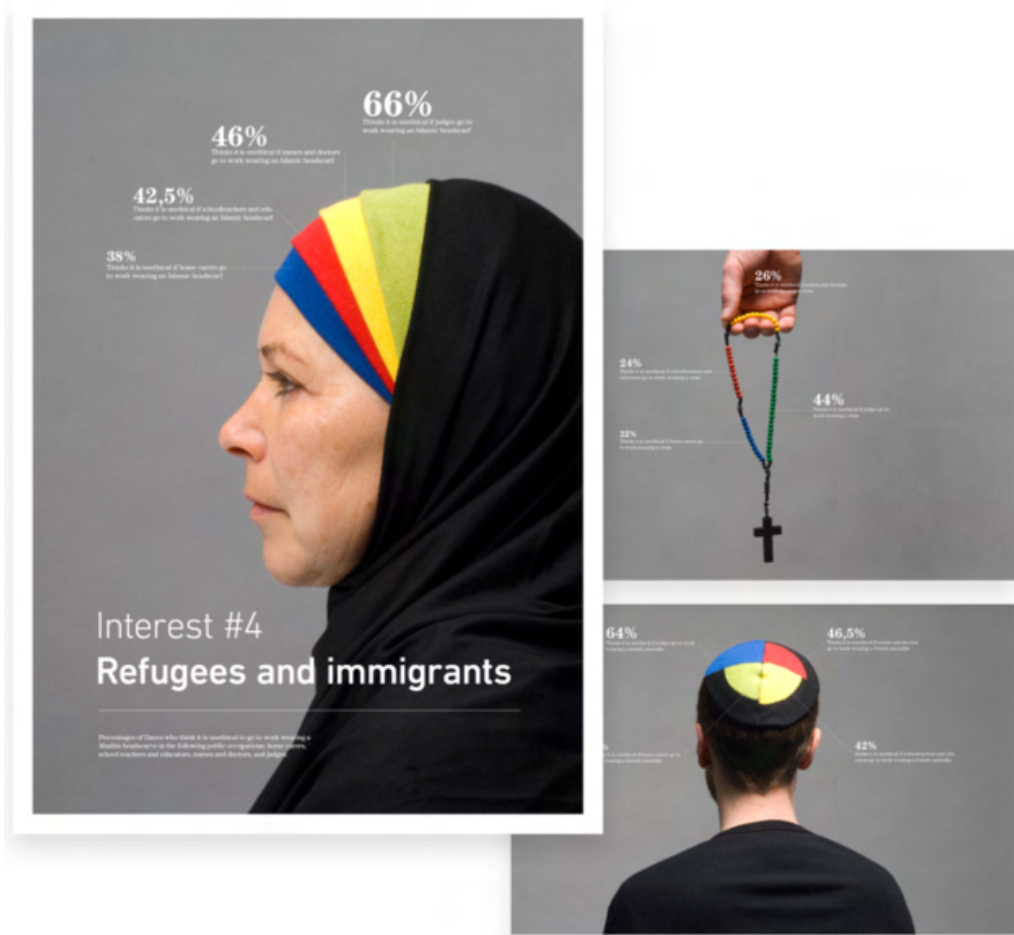


Figure 3.25: Infographics in Context [Ørntoft, 2011]

The photographs show individuals wearing or holding religious items, and overlays percentages indicating what portion of the Danish population deems it unethical for a person in certain professions to wear these symbols.

By merging numbers with actual objects, abstract percentages are more tangible and immediate. The viewer grasps not only the quantity of the data but also its human and material dimensions.

Data alone often lacks the capacity to evoke empathy, but pairing quantitative metrics with metaphors makes it possible to create a narrative that helps individuals connect intellectually and emotionally to the data being shown.

Data visualization in awareness campaigns is about more than aesthetics, it can be a powerful instrument to highlight urgent social, environmental, and humanitarian challenges.

The classifications were made mainly on the realms of **Context**, **Interactions** and **Structure**, based on the classification proposed by [Bae et al., 2022], where it was suggested that the categorization of physicalizations should take into account a wide array of features. The table takes into account the following classifications:

Category	Classification
Purpose	Reflection, Enjoy, Contemplate, Analyse, Education
Public	General, Creators, Researchers, People with Disability, Children, Students
Setting	Museum, Installation, Unknown, Private, Educational
Data Source	Where the data was acquired
Sense	Visual, Haptic, Sound, Taste, Smell
Interaction Method	Directed, Indirect, Sensed, GUI
Interaction Type	Passive, Active
Form Factor	How the data takes form in the environment (e.g., projection, physical installation, jewelry)
Data Form	Color, Position, Form, Light, Volume, Texture, Vibration, Motion
Material Used	Specify materials utilized in the project
Mobility	Fixed, Portable
Scale	Low, Medium, High
Temporal Nature	Persistent, Ephemeral, Permanent
Relevance for Dissertation	None, Low, High, Very High

Table 4.1: Summary of Categories and Details

In this section, the entire table will not be discussed in detail. Instead, the focus will be on cases related to sensibilization and awareness campaigns, especially those that integrate data visualization or physicalization to communicate. Some are related to space debris, but not all of them, being more related to awareness campaigns about other subjects.

4.2 Satellite Lamps



Figure 4.2: Satellite Lamps [Einar Sneve Martinussen and Arnall, 2012]

A project created by Einar Sneve Martinussen, Jørn Knutsen, and Timo Arnall[Einar Sneve Martinussen and Arnall, 2012] is an example that merges data from satellites with physical objects that exist in everyday spaces. The central concept is to make the normally invisible infrastructure of satellite networks visible, in this case, by focusing particularly on GPS signals and translating these signals into a visual medium. The project uses custom-built lamps that light up when GPS signals are detected, turning these transmissions into a perceivable phenomenon.



Figure 4.3: Satellite Lamps patterns over time [Einar Sneve Martinussen and Arnall, 2012]

Satellite signals are everywhere in our lives, enabling everything from navigation to communication, but they remain largely unseen. The Satellites Lamps project transforms this invisible infrastructure into a piece that can be seen. According to the authors, the lamp prototypes incorporate a GPS receiver (EM406), a microcontroller to act as a GPS Evaluation Shield, and a light bulb. When a satellite passes over, and the receiver locks onto its signal, the lamp glows or shifts in intensity. The system encodes real-time data about satellite presence and the strength of signals into brightness levels of light. From a classification perspective, we can look at this project in terms of (Table 4.2):

Category	Classification
Purpose	Education, Reflection.
Public	General.
Setting	Installations.
Data Source	Real-time satellite GPS signals.
Sense	Visual.
Interaction Method	Indirect. The user does not manipulate the data but sees real-time changes.
Interaction Type	Passive. Observers can only watch the changes in light patterns.
Form Factor	Lamps.
Data Form	Brightness of the lamps.
Material	Lamps, electronics, satellite signal receivers.
Mobility	Fixed or portable, depending on where the lamp is placed.
Temporal Nature	Persistent.

Table 4.2: Classification of Satellite Lamps Installation

In an awareness context, this project succeeds in making an intangible phenomenon (satellite signals) not just visible but physically embodied in an everyday object, bridging the gap between advanced technological infrastructures and shared human experience.

4.3 Orbacles



Figure 4.4: Orbacles [TEN x TEN, 2017]

Orbacles is a set of three large, spherical installations created by TENTEN Studio in collaboration with MINN LAB [TEN x TEN, 2017]. These “orbacles” uses data about how climate change is reshaping bird species distribution in Minnesota.

Each dome corresponds to a specific temporal or emissions scenario, reflecting the present and two possible futures, one where the emissions are larger and the other where the emissions are lower. In total, the sculptures incorporate 147 bird species prevalent in the city of Minnesota:

- **Orbacle A (Bird House):** Represents the current bird populations. The “birdhouse” modules are filled with nesting materials and hidden speakers that play recorded bird sounds powered by solar panels;
- **Orbacle B (Bird Food):** Envisions a future scenario under low emissions projections for the year 2100. Each module becomes a bird feeder stocked with seeds and grains, and are activated with diffusers that release scents;

- **Orbacle C (Bird Bath):** Depicts a future scenario under high emissions by 2100. The modules function as birdbaths filled with water, which overflows and drips to the ground below, misters cool the air for birds and visitors.

Across all three orbs, each bird species is represented by a “module location” but adapted to the module’s function (house, feeder, or bath). The size of each module’s “hood” is proportional to the length and wingspan (the distance between the ends of the wings of a bird) of the species. The color changes between the *Orbacle A* and the two future orbs shows the species projected to be more (blue) or less (orange) prevalent under each emissions scenario (Figure 4.5).

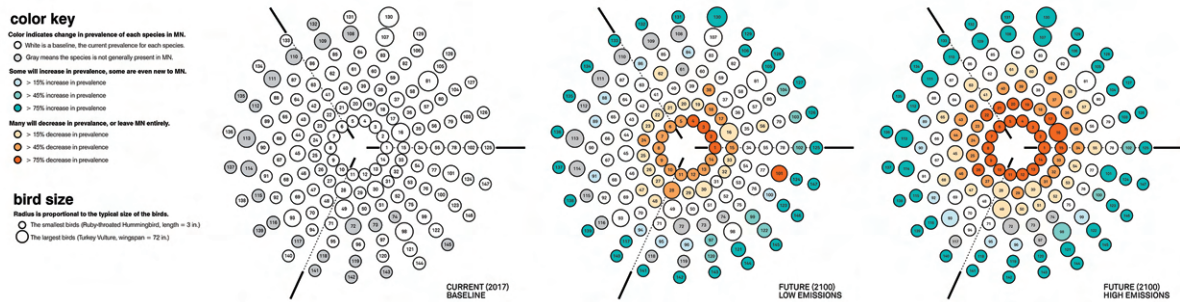


Figure 4.5: Orbacles visual encoding [TEN x TEN, 2017]

Throughout the summer and fall exhibition, *Orbacles* also had a special event for the Northern Spark festival, where a digital projection animation that mapped virtual “bird flocks” onto the orbs was used (Figure 4.6).

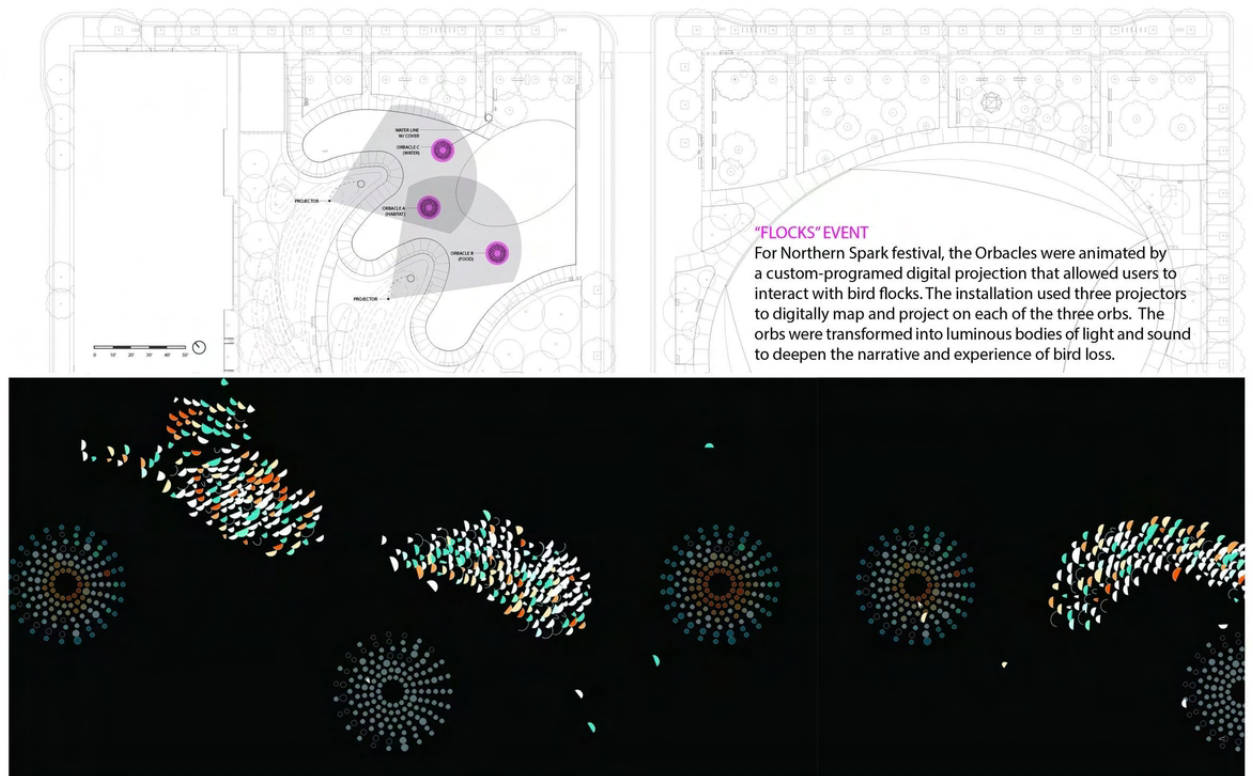


Figure 4.6: Projections created during the Northern Spark Festival [TEN x TEN, 2017]

From a classification perspective, we can look at this project in terms of (Table 4.11):

Category	Classification
Purpose	Reflection, Education, Contemplate.
Public	General.
Setting	Installation.
Data Source	Environmental data.
Sense	Visual, Sound, Smell, and Haptic. Visual for the colors, sounds and smell to immerse the public, haptic due to the bath module that drops water on the ground below.
Interaction Method	Indirect, though during the festival there was a more guided exploration with the projections.
Interaction Type	Passive.
Form Factor	Physical domes.
Data Form	Color, position, and sometimes motion changes in the projected images.
Material	Plastic, metal hoods, wooden boxes, rigid structures, integrated electronics.
Mobility	Fixed.
Temporal Nature	Ephemeral.

Table 4.3: Details of Environmental Data Installation

This project exemplifies how data physicalization can communicate scientific research through a combination of artistic expression, interactive design, and environmental storytelling.

4.4 Perpetual Plastic

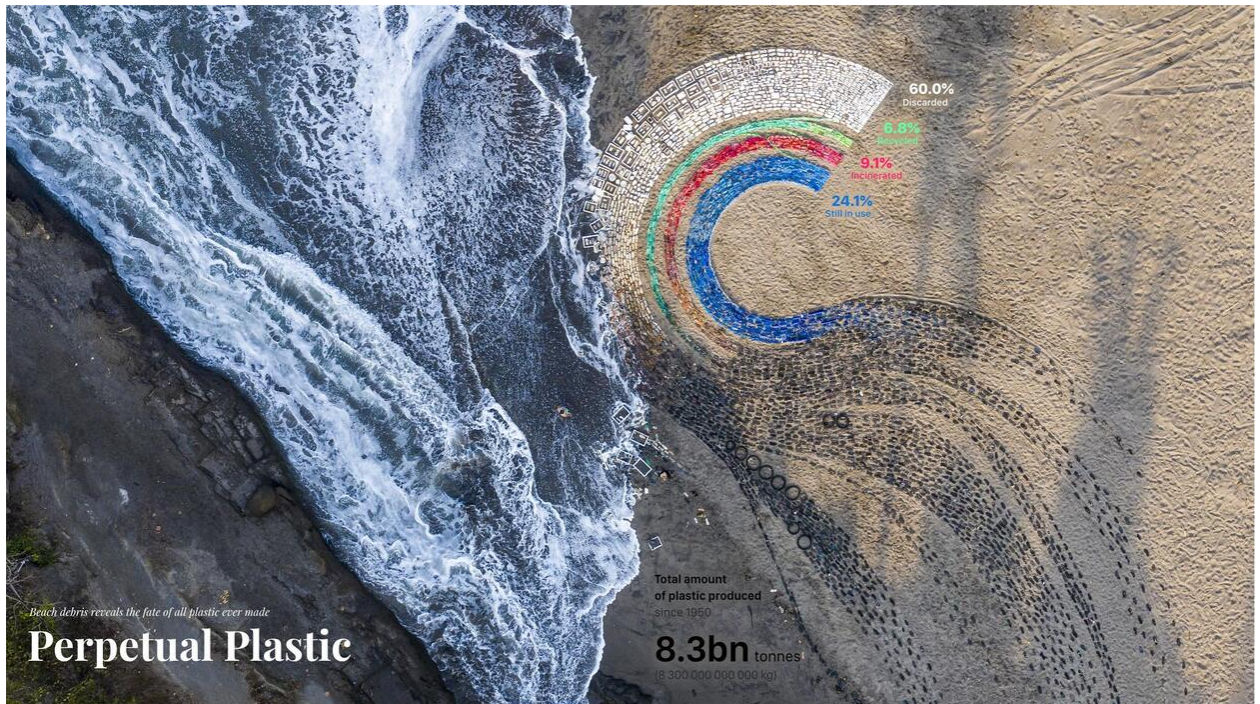


Figure 4.7: Perpetual Plastic [Liina Klauss and Stefaner, 2021]

Perpetual Plastic is a physical data sculpture made from beach debris, leaving the fate of all plastics ever produced. It is a large-scale data sculpture that draws attention to the global plastic pollution crisis, focusing on the large amounts of plastic waste in the ocean. Created by Liina Klauss, Moritz Stefaner, and Skye Morét, the project was created on a beach in Bali, Indonesia, where considerable amounts of plastic debris land on the shore daily [Liina Klauss and Stefaner, 2021]. The artwork shows the fate of all plastics ever produced since the 1950s, totaling around 8.3 billion tonnes, and how these plastics end up being discarded, incinerated, still in use, or recycled.

One of the distinctive elements of Perpetual Plastic is that it uses beach debris collected locally as the “building blocks” for the sculpture. Each piece of waste is grouped and arranged based on color-coded categories, representing different outcomes of the billions of tonnes of Plastic manufactured throughout modern history.

The sculpture acts as both an information display and an ephemeral installation. Ephemeral because the weather conditions slowly degrade and disperse some of the pieces. The environment co-participates in the design.

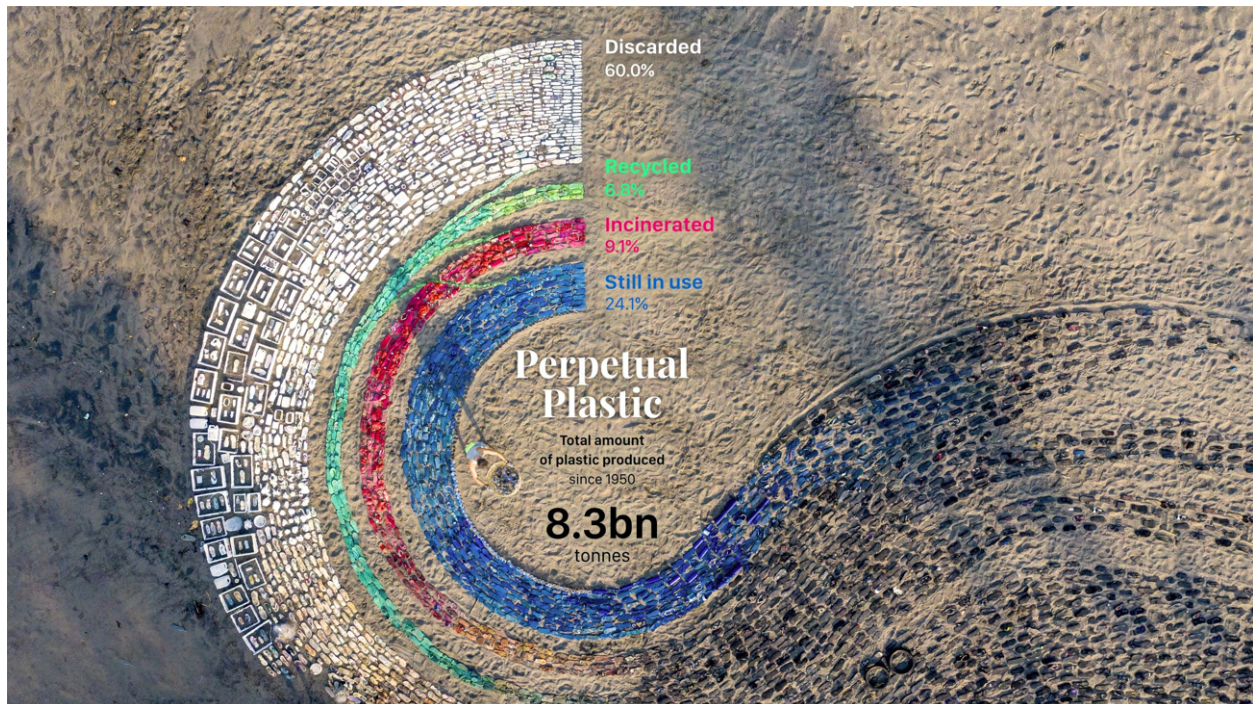


Figure 4.8: Perpetual Plastic [Liina Klauss and Stefaner, 2021]

Much like other environmental projects, Perpetual Plastic serves as an awareness campaign. In the short time it was on display, the sculpture sparked conversation among tourists, local communities, and governmental agencies, calling attention not just to the problem but to potential strategies for mitigating it.

From a classification perspective, this installation can be summarized as (Table 4.4):

Category	Classification
Purpose	Reflection, Contemplation, Education
Public	General
Setting	Outdoor installation (beach)
Data Source	Global plastic production data
Sense	Visual
Interaction Method	Indirect
Interaction Type	Passive
Form Factor	Arcs on the ground made of categorized plastic
Data Form	Color encoding, arrangement (arc lengths)
Material Used	Found plastic debris, paint
Mobility	Fixed
Temporal Nature	Ephemeral

Table 4.4: Classification of Perpetual Plastic

Perpetual Plastic exemplifies how large-scale physical installations can serve as a “wake-up call”. Although it focuses on marine pollution rather than space de-

bris, the similarities in approach, making invisible problems visible through data, highlight the versatility of data physicalization as a method for awareness.

4.5 Air Transformed



Figure 4.9: Air Transformed [Posavec, 2014]

Air Transformed is a project by Stefanie Posavec in collaboration with other partners interested in exploring air quality. The project aimed to convert complex air pollution data from Sheffield (UK) into physical and wearable objects, making the pollution tangible and personal [Posavec, 2014].

Unlike a static sculpture, this project consists of two physical artifacts. One of the central premises is that pollution data can be “worn,” turning the body into a canvas for the data. While air pollution numbers are usually measured with scientific instruments and seen on specialized websites that uses abstract charts, this approach made it possible to bring them into everyday life through an appealing design form.

Some of the key elements of Air Transformed are:

- **Necklaces:** Every week is divided into one segment for every six hours (morning, afternoon, evening, and night). Each piece is shaped according to

the average PM_{10} level recorded in that interval, with smoother, smaller segments representing lower pollution and larger, spikier segments at higher levels.

- **Glasses:** On every lens, the pattern size directly encodes pollutant concentration: larger symbols indicate higher pollutant levels, clouding the vision. Each lens focuses on a single type of pollutant, and annotations of each pollutant's absolute and relative concentrations are included.

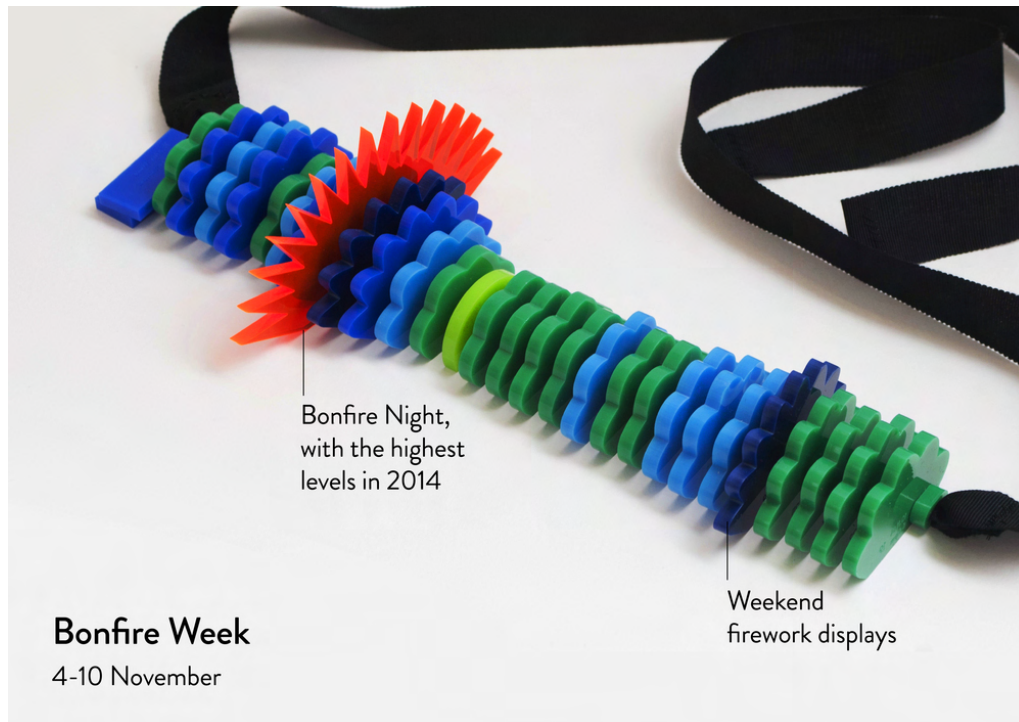


Figure 4.10: Air Transformed [Posavec, 2014]

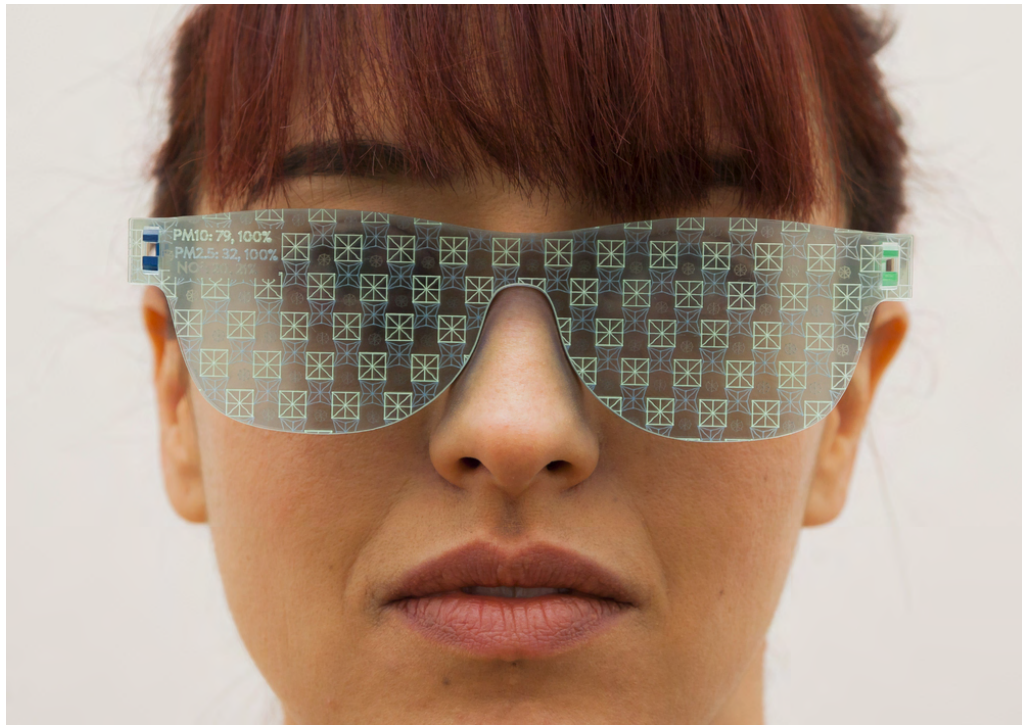


Figure 4.11: Air Transformed [Posavec, 2014]

In terms of classification, Air Transformed can be (Table 4.5):

Category	Classification
Purpose	Reflection, Education, Contemplation
Public	General, People with visual disability
Setting	Private, Educational
Data Source	Air quality data (NO ₂ , CO ₂ , PM levels) for Sheffield, UK
Sense	Visual and Haptic
Interaction Method	Direct, sensed
Interaction Type	Active
Form Factor	Necklaces and glasses
Data Form	Color, position, form and texture
Material Used	Acrylic
Mobility	Portable
Temporal Nature	Persistent

Table 4.5: Classification of Air Transformed

This project shows how data about an invisible phenomenon can be translated into meaningful objects that stimulate reflection and conversation, especially how things can be transformed into objects that can be wearable and have a new meaning with them.

4.6 Visualizations related to Satellite data

A few projects stand out when it comes to visualizations that focus on satellites and space debris. While they are not physicalizations, they still use the data-driven design principles discussed previously. These examples are relevant as awareness visualizations and references for physicalizations on space debris.

4.6.1 Satellite Surge

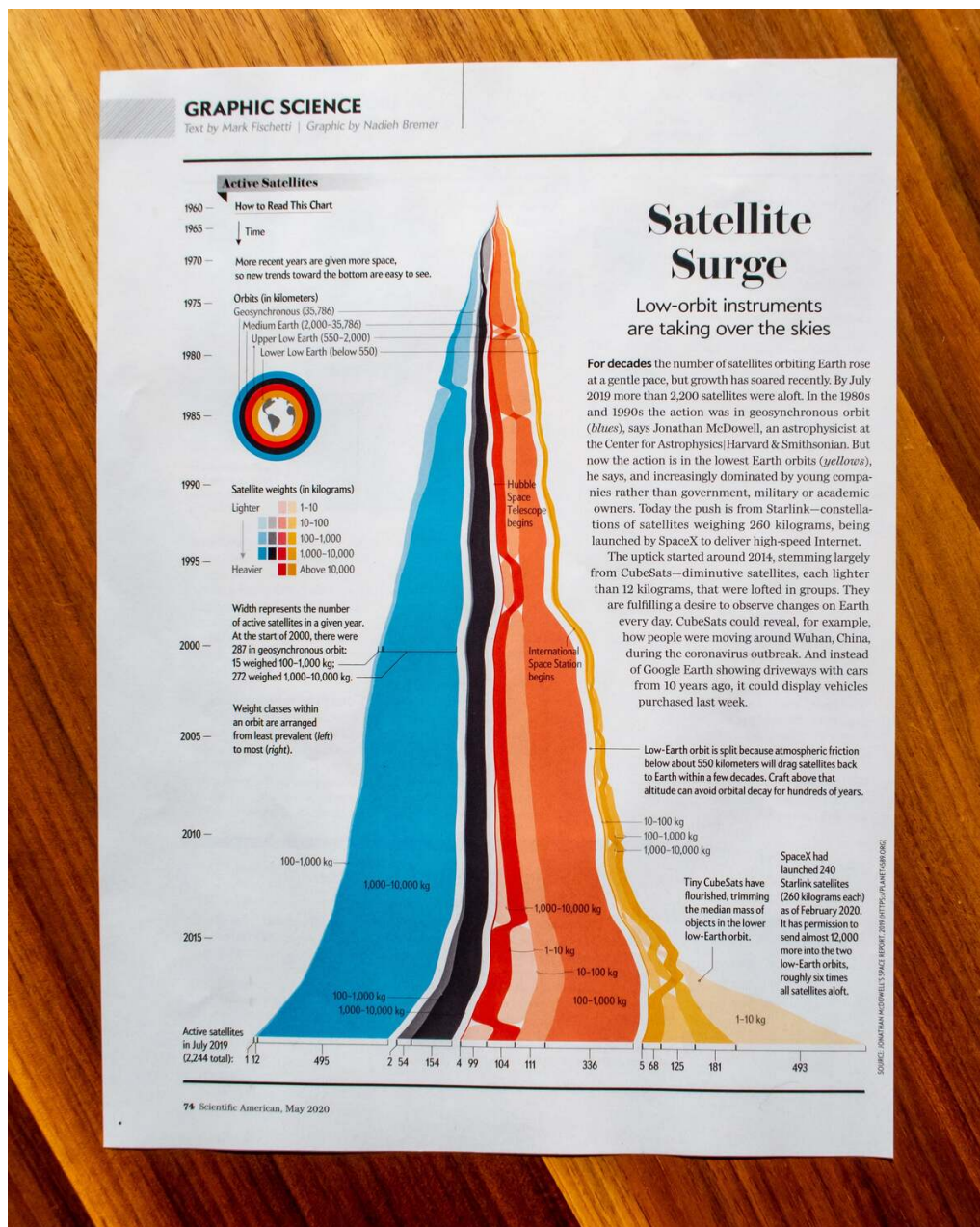


Figure 4.12: Satellite Surge [Bremer, 2020]

Satellite Surge is a data visualization project by Nadieh Bremer for Scientific American [Bremer, 2020]. The main goal behind the visualization is to illustrate the dramatic increase in the number of satellites orbiting the Earth, focusing on the exponential growth of low-Earth orbit (LEO) satellites to the proliferation of planned “mega-constellations” such as Starlink.

The article and visualization aim to raise awareness about the scale and speed of satellite launches. The visualization captures the relationship between satellite mass, orbital altitude, and epoch.

The data behind the project uses publicly available sources like the Union of Concerned Scientists and the Center for Astrophysics (Harvard & Smithsonian) catalogs. The chart resembles a mountain-like shape that accumulates over time, combining a streamgraph and bump chart. The width of each “slice” on the horizontal axis is proportional to the number of satellites in that class for each year. At the same time, the vertical expansion shows a historical progression from 1960 onward.

This piece shows how lower orbits are now heavily populated, even if it does not show anything about space debris, it still emphasizes that these regions are getting crowded.

4.6.2 Space Wars

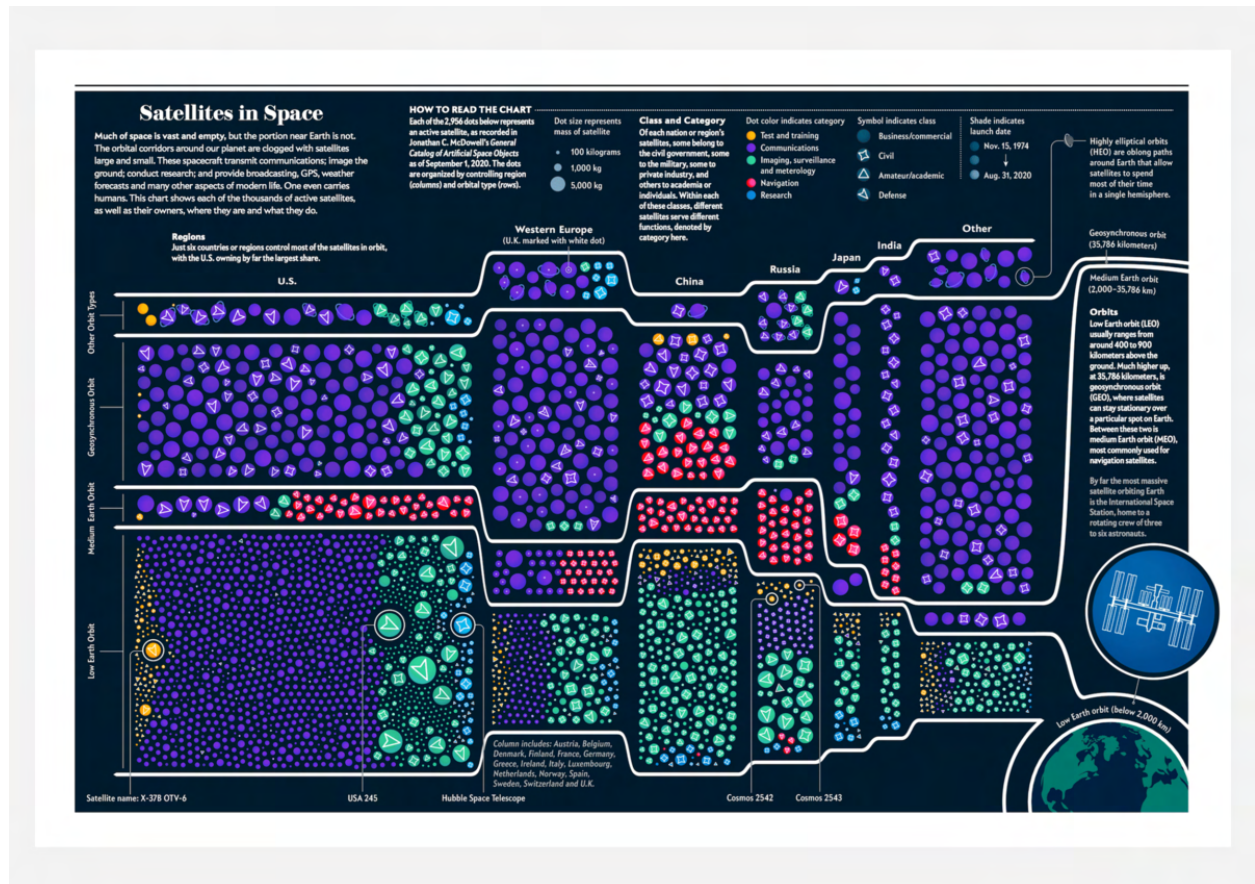


Figure 4.13: Satellites in Space [Nadieh, 2020]

Another visualization by Nadieh Bremer is *Space Wars* (Figure 4.13), also published on *Scientific America* [Nadieh, 2020]. Unlike *Satellite Surge*, which focuses on the rise of satellites' launches, *Space Wars* emphasizes the geopolitical distribution of satellites: which countries own them and their main functions.

The data also comes from the Union of Concerned Scientists, the author organizes satellites in columns by their orbital type (Low Earth Orbit, Medium Earth Orbit, Geostationary Orbit, Highly Elliptical Orbit, and Others) and in rows by region or country (U.S., China, Russia, Japan, India, Western Europe, etc.). Within each cell, the shapes (circles, triangles, squares) convey the main use of the satellite: communication, imaging/surveillance, research, navigation, defense, and so forth. The dot size encodes the mass, and the launch date is suggested by color intensity or shading from older to more recent times.

While *Space Wars* does not depict defunct satellites or orbital debris, it provides a lens into global satellite “ownership” and how crowded certain orbital regions have become.

Space Wars provides a creative way for visually handling multiple data dimensions, mass, orbit, function, and ownership, in a single cohesive layout.

4.6.3 SpaceTrashSigns: The Broken Compass

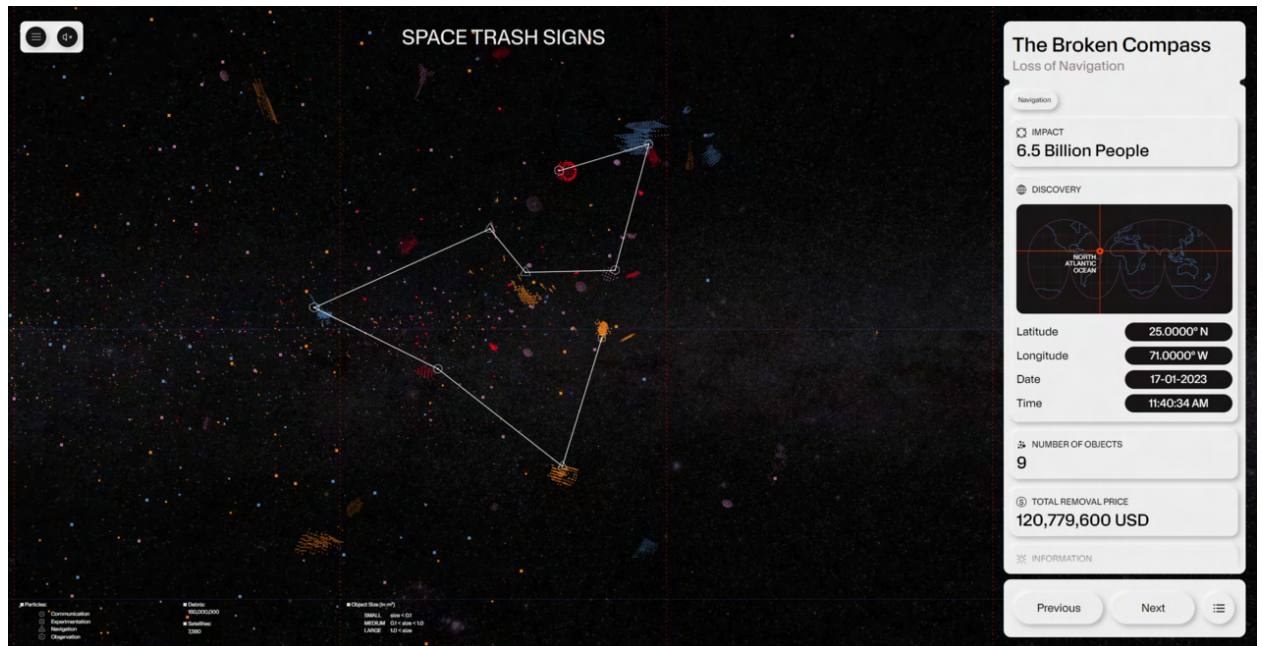


Figure 4.14: Space Trash Signs [BrokenCompass, 2020]

SpaceTrashSigns is an ongoing project that uses a constellation-based approach to highlight the societal consequences of unchecked space debris. One of its scenarios revolves around the hypothetical aftermath if collision events compromise a good portion of the navigation satellite infrastructure [BrokenCompass, 2020].

This scenario is purely digital, intended to capture the public’s attention. Large points in space represent dead satellites and debris fragments, with lines connecting them to form “constellations”. Each constellation is a metaphor for a specific threat from large amounts of debris. The narrative explains that if collisions multiply, the ability of satellites to provide accurate GPS or GNSS (Global Navigation Satellite Systems) signals might degrade or vanish entirely.

The user can rotate and zoom in the 3D environment, focusing on collisions, orbits, or object sizes. The interface merges a futuristic storyline with real baseline orbital data, bridging science fiction and some level of scientific modeling.

The Broken Compass is explicitly designed to raise awareness about space pollution. Instead of focusing on the number of satellites launched or their distributions, it offers a grim hypothetical scenario: If critical navigation satellites were to be taken offline by debris collisions, billions of people would feel the impact, from shipping and agriculture to smartphone navigation and emergency services.

4.7 Discussion

All of the cases explored, whether they relate directly to satellites or to wider environmental and social issues, share a common theme: they try to make invisible and abstract data more tangible, meaningful, and accessible. By doing so, they create a narrative around the numbers, allowing viewers to perceive and maybe even feel the impacts behind them. Even though some of these examples are two-dimensional visualizations and others are large-scale sculptures or immersive installations, each one highlights the power of data-driven storytelling. In the context of an awareness campaign, be it about space debris, plastic pollution, or air quality, a well-crafted project does more than just convey statistics: it provides a medium for emotional engagement, critical reflection, and action.

One of the similarities of projects like Satellite Lamps, Air Transformed and Orbacles is their emphasis on multisensory engagement. Even though each one of them uses data in different ways, they all move beyond a just visual experience. That approach expands the audience's ability to connect with the message. Instead of simply "looking" at data, viewers can also feel or hear it.

These projects also highlight the importance of context to better convey their messages. Perpetual Plastic, for example, took place on a beach in Bali where debris physically washes ashore. Orbacles is also tied to the environment where it was installed, with each dome reacting to or showing different "futures" for bird species in Minnesota.

Another parallel is how metaphors can be used to communicate. The Broken Compass uses constellations to show how collisions might disrupt navigation and life for billions of people. Air Transformed uses wearable artifacts as a metaphor for personal involvement, such as a necklace that can be heavy on the person depending on the air quality.

All of these projects show how data-based experiences can start conversations. Orbacles invites dialogues about bird conservation and climate change, Perpetual Plastic starts discussions about waste management, Satellite Lamps turns the invisible GPS signs into a living illustration of the satellite networks we rely on, the Broken Compass scenario frames space debris in a way that reveals its tangible impact. This is key for an awareness campaign: using accessible metaphors that convey how society might be affected if these problems are not addressed.

Another insight from these projects is that the interaction can be active or passive. In both cases, the question becomes: "How should a participant engage with the data most meaningfully?" It can also influence how long a physicalization can last if it will be something ephemeral or just used many many times.

Overall, these examples show many different strategies to create an interesting data physicalization to raise awareness. Using good metaphors, using more than one sensory channel and consider their interactions. For space debris, where the problem is vast and invisible to our daily lives, having these considerations can help transform lines on a chart into a tangible experience that motivates public dialogue and a positive change.

Chapter 5

Preliminary Work

This chapter presents the initial experimentation phase, including data gathering, analysis, an overview of how the Two-Line Element (TLE) works, and artifacts created.

5.1 Data Gathering

The data used came from many sources, many of which used the TLE dataset. Initially, the TLE format was a challenge to understand, but to have some experiences and test how some graphics would work in a 3D printer, a more straightforward database was used, the intent was to explore some of the data and explore the possibilities of 3D printing for this data, in this stage there were no goals of what should be represented. The source of the first used data was the Annual number of objects launched into space [UNOOSA, 2024] dataset, which has information about the number of objects launched into outer space annually, categorized by country and number of launches per year. This dataset also included an entity named "World" among the countries.

Later on, the Celestrak dataset [Celestrak] was used, this dataset employs the TLE format and provides more comprehensive data about the satellites. This allowed for further exploration beyond the number of launches per year, as the TLE format contains more detailed information. However, the Celestrak dataset has some limitations, while it includes information about space debris, it only details two specific satellite-produced debris from a collision in 2009. These debris are still being tracked to this day. Since the main focus is to raise awareness about space debris, relying on data from just two objects is insufficient. For that reason, the TLE format in this dataset was explored to understand how to read this format, but alternatives that could provide a complete overview of space debris were searched.

Another data source was Space-Track.org [SpaceTrack], which contains data about a more significant number of debris beyond those formed from satellite collisions. The data is in a JSON format and offers more detailed information. Although it uses the TLE format, the data is categorized rather than presented as raw num-

bers, providing all the information contained in the TLE along with additional debris data and a few more categories, such as the size of the launched object and type.

Later on, a dataset from the Union of Concerned Scientists [Scientists, 2023] was found. This database offers extensive data, including information about operators, satellite usage (commercial, communication, etc.), purpose, class of orbit (also present in the TLE dataset, though some calculations are required for the classification), type of orbit, mass, and expected lifetime, among others. Unfortunately, this dataset was identified after other datasets had already been explored. Still, it provides a lot of data unavailable in the other mentioned sources, including pre-calculated values such as the orbital region.

5.2 Data Analysis

This section describes some of the analyses that were conducted, a few explorations of the different datasets, and the creation of graphics for exploratory purposes.

5.2.1 Two-Line Element (TLE) Data

The Two-Line Element (TLE) format has its roots in the early days of the Space Age, dating back to the 1960s. In the United States, the North American Aerospace Defense Command (NORAD) was responsible for monitoring and cataloging all objects orbiting Earth, which led to the development of this format.

The two-line structure is a result of the limitations of punch cards and the desire to keep each object's data on a single pair of lines, making them easy to handle [Kelecy et al., 2007]. This structure remains intact and is used to this day.

The TLE format consists of two lines of data for each satellite or piece of debris (Figure 5.1). The first and second contain fields aligned to fixed columns. These fields have the orbital parameters for predicting an object's position and speed around Earth, including inclination, eccentricity, right ascension of the ascending node, argument of perigee, mean anomaly, mean motion, and a drag term known as BSTAR. Table 5.1 provides a condensed overview of the main fields in a TLE.

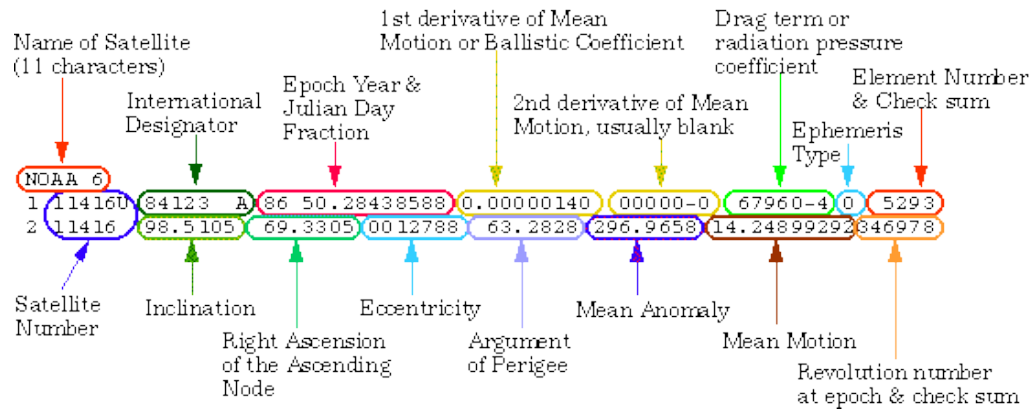


Figure 5.1: TLE Dataset [Kaitlyn, 2020]

Table 5.1: TLE Dataset Fields Details

Line 1	Description
Line Number	Identifies the first line of the TLE as "1".
Satellite Catalog Number	A unique number assigned to each satellite.
Classification	Shows if the satellite is classified or not: U (Unclassified), C (Classified), S (Secret).
International Designator	Information about the satellite's launch: year, launch number, and piece identifier.
Epoch	The date and time when the TLE was created.
1st Derivative of Mean Motion	Indicates how the satellite's speed is changing over time.
2nd Derivative of Mean Motion	Shows the acceleration of the satellite's speed.
BSTAR Drag Term	Estimates the effect of Earth's atmosphere slowing down the satellite.
Ephemeris Type	Specifies the version of the orbital model used.
Element Set Number	A number that increases each time a new TLE is issued for the satellite.
Checksum	A single-digit number used to verify the TLE's accuracy.
Line 2	Description
Line Number	Identifies the second line of the TLE as "2".
Satellite Catalog Number	Repeats the unique number from Line 1.
Inclination (deg)	The tilt of the satellite's orbit compared to Earth's equator.
Right Ascension of the Ascending Node (deg)	The horizontal angle where the satellite crosses the equator going north.
Eccentricity	Describes the shape of the satellite's orbit (how circular or elliptical it is).
Argument of Perigee (deg)	The point in the orbit closest to Earth.
Mean Anomaly (deg)	The position of the satellite in its orbit at the epoch time.
Mean Motion (rev/day)	How many times the satellite orbits Earth each day.
Revolution Number	Counts how many orbits the satellite has completed since launch.
Checksum	A number used to verify the TLE's accuracy.

5.2.2 Data Processing

Annual Number of Objects Launched into Space dataset

The first experiments were conducted using the Yearly number of objects launched into outer space dataset [UNOOSA, 2024], which includes only the countries, launches per year, and the country code. The data was analyzed entirely in Python using *Pandas*, *Matplotlib*, and *NumPy*. The first visualization created was a line chart (Figure 5.2) to understand the evolution of the number of launches per year.

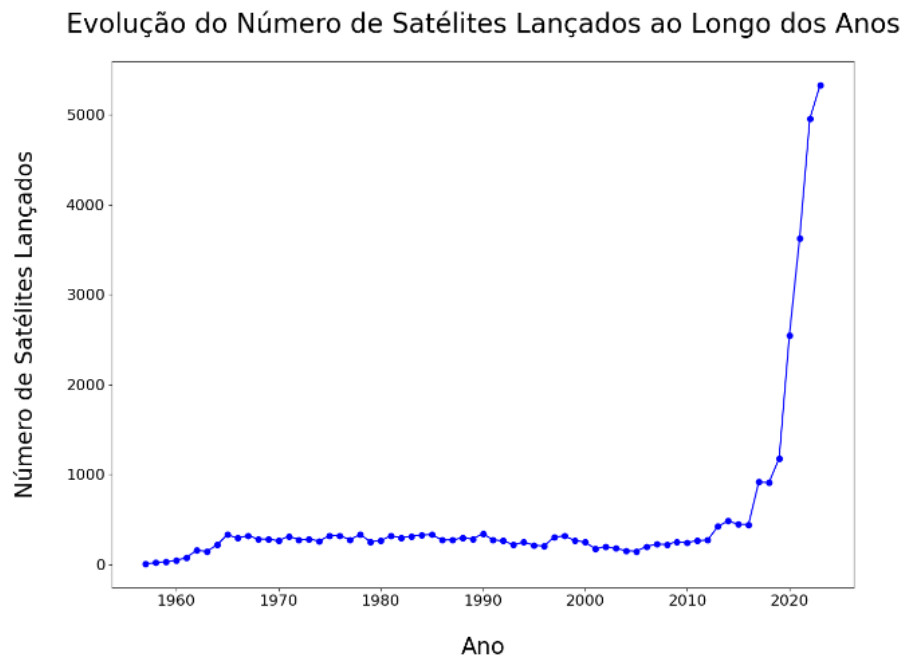


Figure 5.2: Evolution of objects launched during the last 50 years

Another graphic was a bar chart (Figure 5.3) to determine which entities launched the most objects into space, using the total number of launches, where the X-axis represents the countries and the Y-axis represents the total number of objects launched.

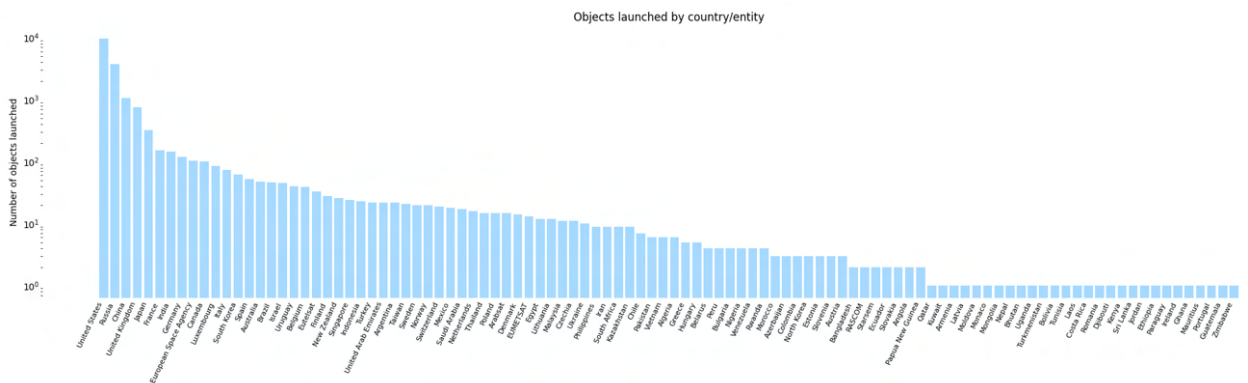


Figure 5.3: Launches by Countries and Entities using logarithmic scale

After more analysis, the countries were grouped by continent to better organize the data (Figure 5.4). Unfortunately, in this dataset, the entity "World" did not provide specific information about individual countries, so it remained as a separate entity and had the highest number of launches. In other datasets, this issue does not happen, and satellites are related by their country of origin.

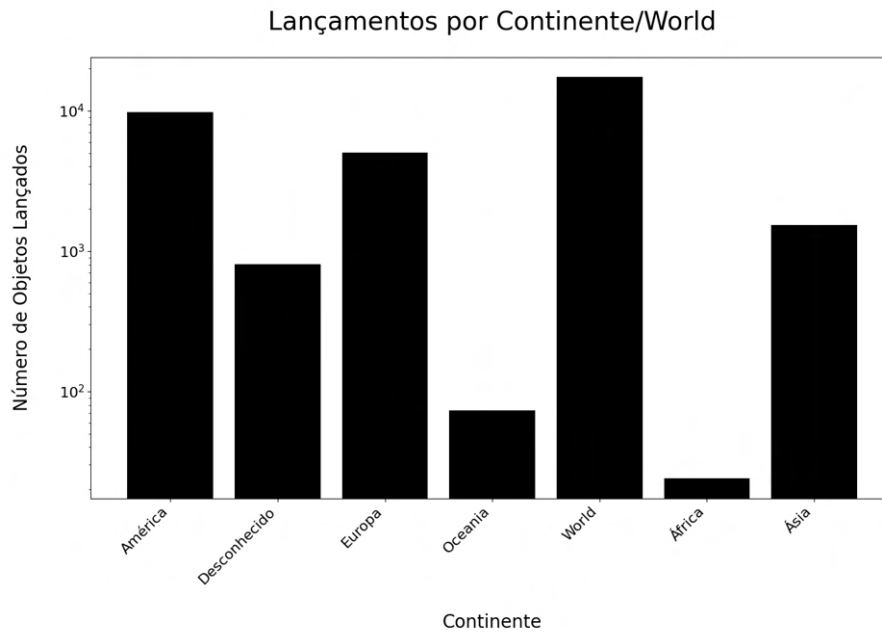


Figure 5.4: Continents/World launches using logarithmic scale

Later on, with the goal of creating something that could become a zoetrope, a 3D circular graphic (Figure 5.5) was made using the three entities with the highest number of launches per year over the last 24 years.

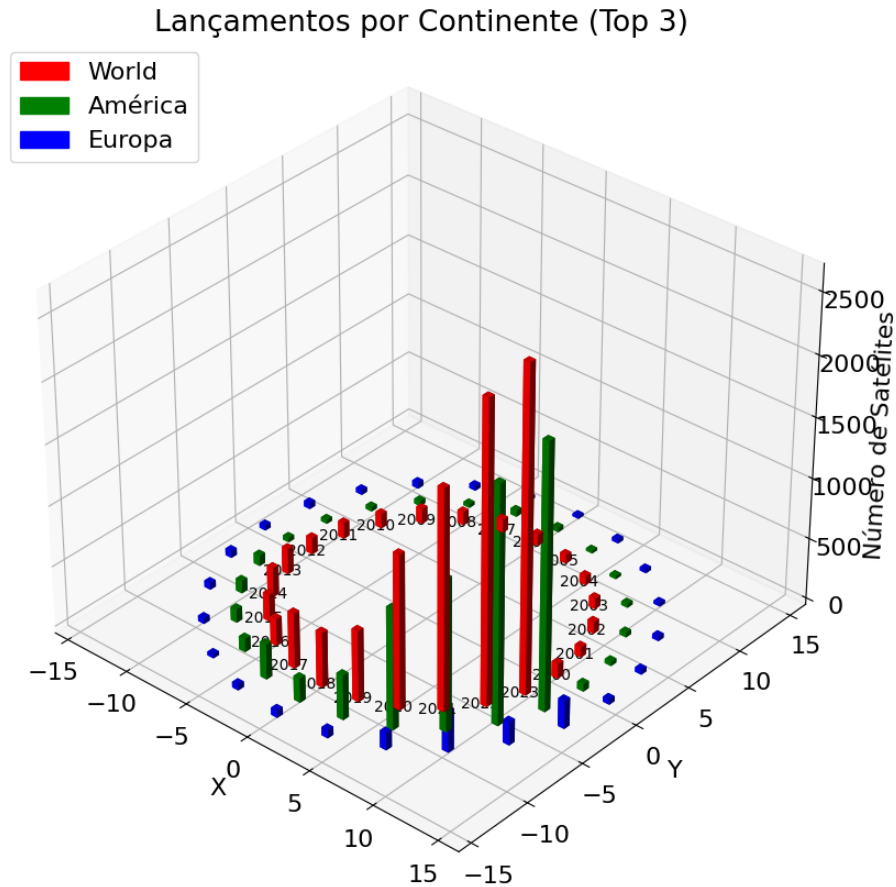


Figure 5.5: Continent launches, the top 3 that launched the most over the last 24 years

Celestrak Dataset

When exploring the data of the Celestrak dataset [Celestrak], the main goal was to decode the TLE format and understand how it worked to visualize the orbits of active satellites around the Earth. Initially, a Python library named *beyond* was used [Pypibeyond]. After using some of the examples to fetch the data and plot one orbit, other methods were employed to visualize all the orbits around Earth with a more exploratory intention, without the goal of making it look too polished, but to see how it would appear with multiple orbits (Figure 5.6).

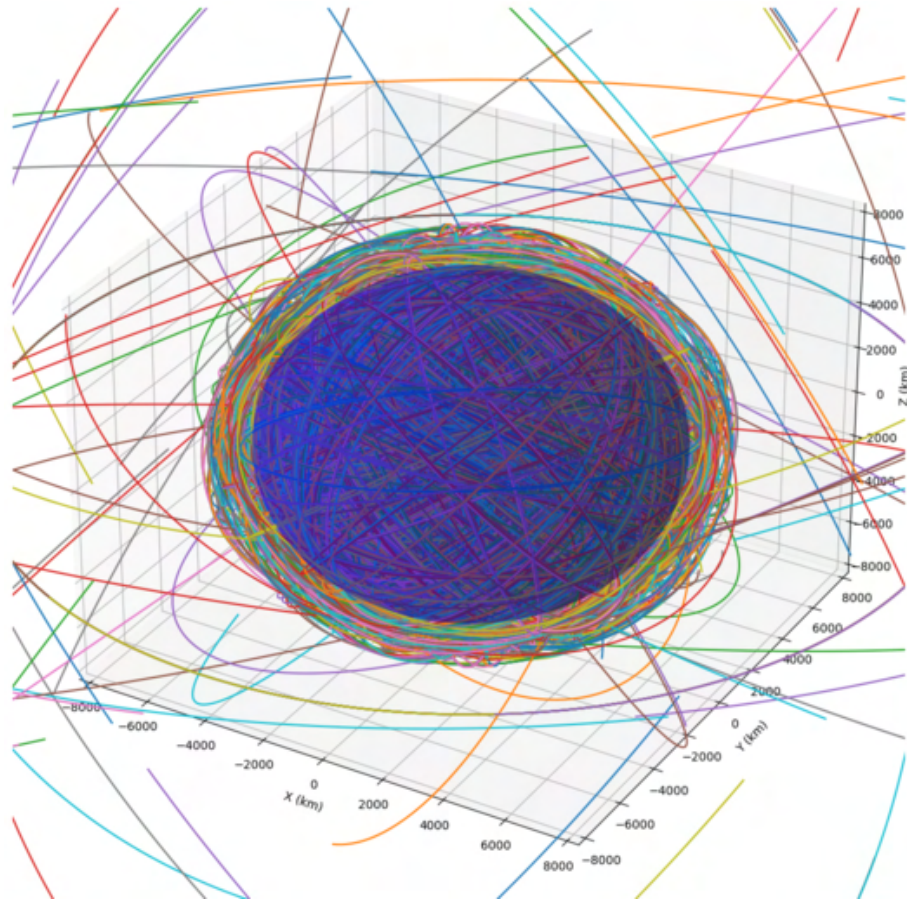


Figure 5.6: All Celestrak orbits around Earth

Initially, the data was fetched directly from Celestrak, and once the data was retrieved, each satellite's information was processed. The SGP4 library [Python] was used, which implements a simplified general perturbations model for orbit prediction [Mukundan and Wang, 2021]. It takes the TLE data and computes the satellite's position in Earth-centered coordinates. The position is then calculated and projected over a certain amount of time, revealing the orbits.

This representation was not intended to be aesthetically pleasing. However, it was driven by curiosity about how it would look if all the orbits of the objects in the Celestrak dataset were displayed. After realizing that the dataset did not include data about space debris besides two satellites that collided, another dataset was searched.

Space-track.org Dataset

The Space-track.org dataset [SpaceTrack] contains information about most objects currently in space, including a significant amount of debris. In addition to the TLE data, it also provides details about the type of object (debris, a payload, a rocket body, or unknown), the object size (small, medium, large), launch date, country code, site of launch, and more. Unfortunately, this dataset does not include the satellite's weight, active status, use, purpose, or expected lifetime,

unlike the dataset from the Union of Concerned Scientists [Scientists, 2023].

Using mainly pandas and matplotlib for the data exploration, this dataset offers more detailed information about the satellites, so the exploration began to identify some relationships. The first exploration aimed to determine the number of objects launched over the years by type (Figure 5.7). A disclaimer is necessary here: not all objects were necessarily launched, as debris is not intentionally launched. Instead, the dates likely represent when some of these objects were detected. The only objects that were truly launched are payloads (satellites) and rocket bodies.

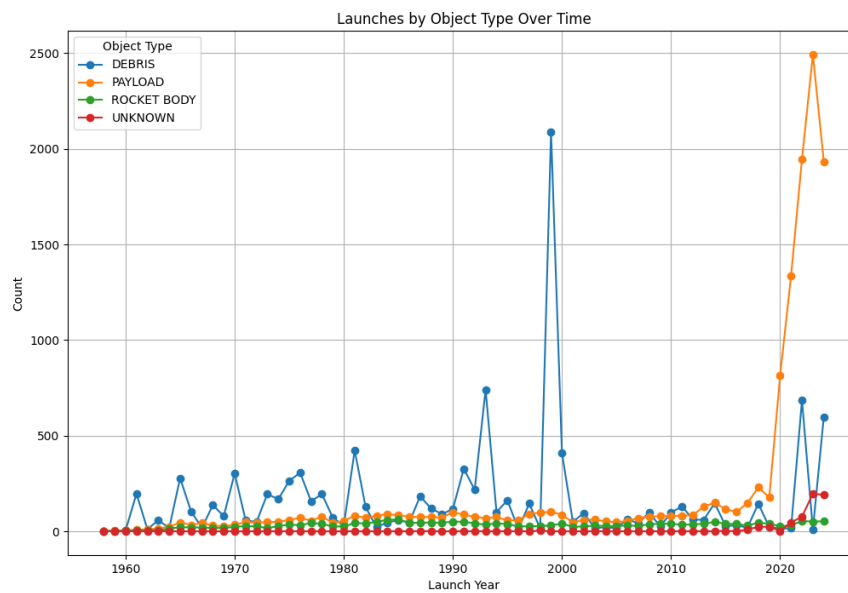


Figure 5.7: Launches along the years by object type

The second analysis, similar to the initial one made with the first explored dataset, was a bar chart showing the countries and the number of objects they launched. Since there is no "World" category (Figure 5.8), it becomes clearer which countries are the most active in sending objects into outer space.

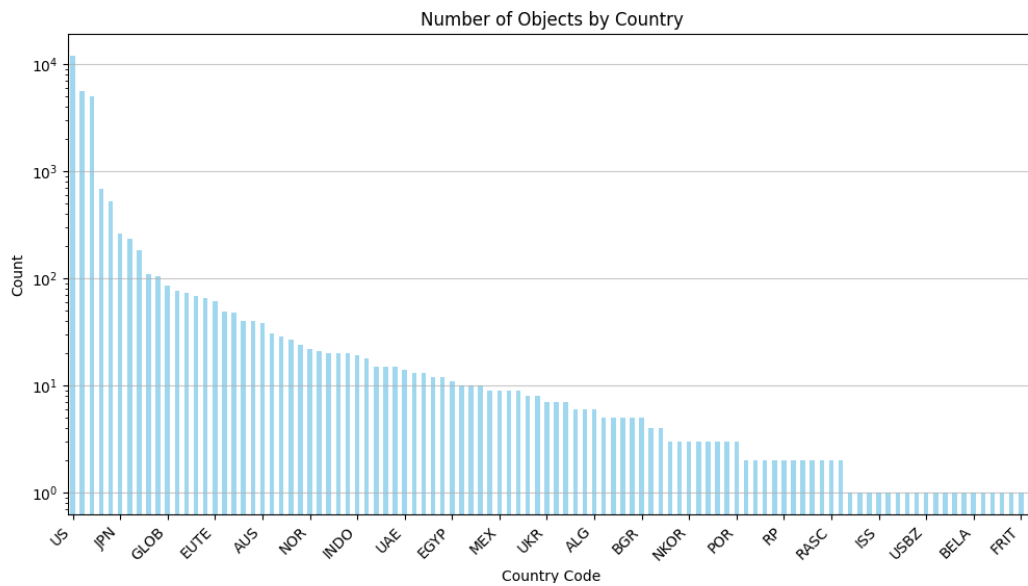


Figure 5.8: Number of objects launched per country using logarithmic scale

Next, the analysis focused on the distribution by object type, the number of objects, and their sizes. The goal was to see which types of objects are more associated with each size category. As expected, most large objects are payloads, all rocket bodies are large, and the majority of small objects are debris.

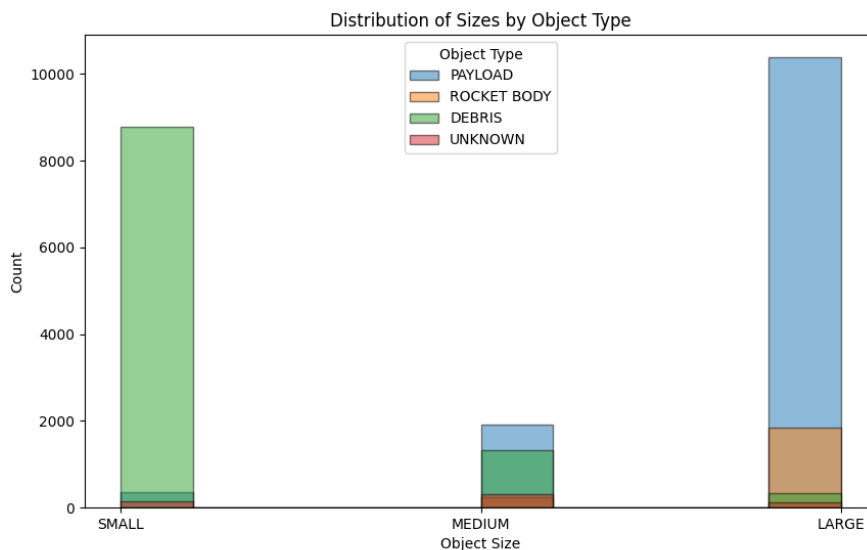


Figure 5.9: Distribution of sizes by types of different objects

Later, inspired by Nadieh Bremer's visualization "Satellite Surge" [Bremer, 2020], a streamgraph was created to observe the evolution of object types over the years. The graphic was designed smoothing the frequency of launches over time and grouping them by object type. It used Gaussian smoothing to even out fluctua-

tions, and each category is represented by a different color. For this graphic, the libraries *pandas*, *numpy*, *matplotlib*, *seaborn*, and *scipy.ndimage* were used.

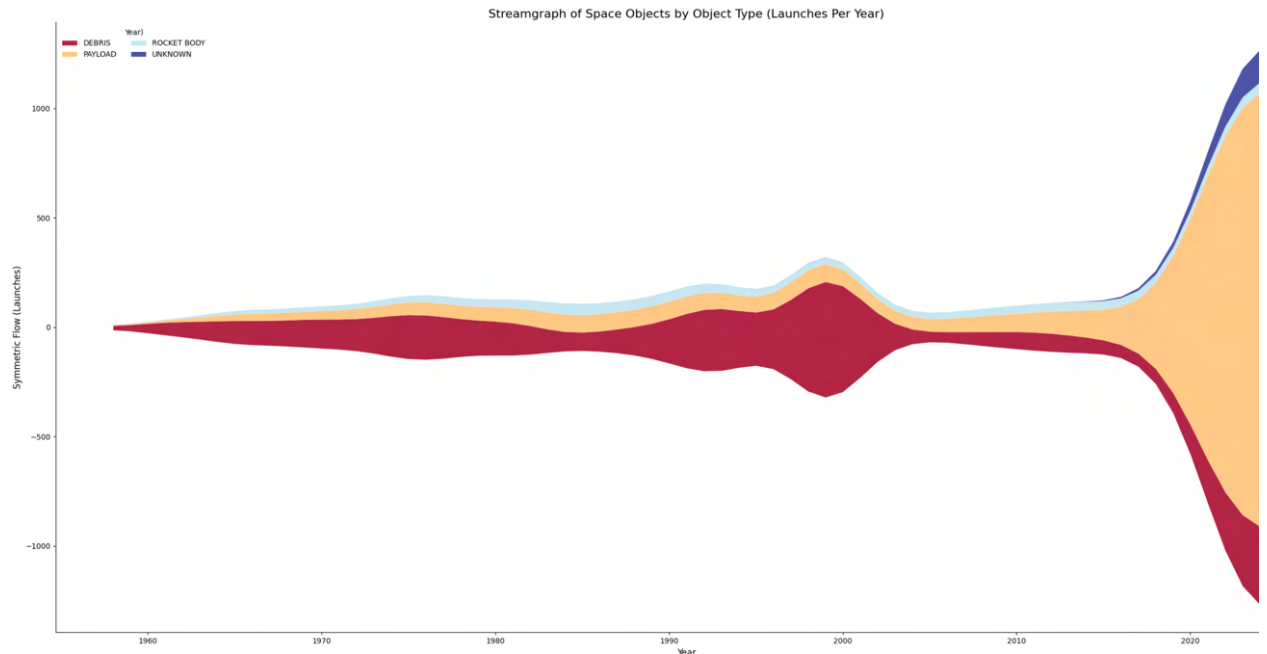


Figure 5.10: Streamgraph of Space Objects by object type

Another analysis was conducted to examine the relationship between the size of objects and their altitude. This included all objects between 200 to 2000 kilometers, aligning the analysis primarily with objects in low (LEO) to medium (MEO) Earth orbits. These altitudes were binned, and the sizes of the objects were also categorized into bins, creating a correlation between size and altitude. A 3D chart was then created (Figure 5.11) using *matplotlib*, where each bar's height represents the number of objects in that specific bin, there was no objects in the very bog cathegory.

Distribuição de Objetos por Altitude e Tamanho

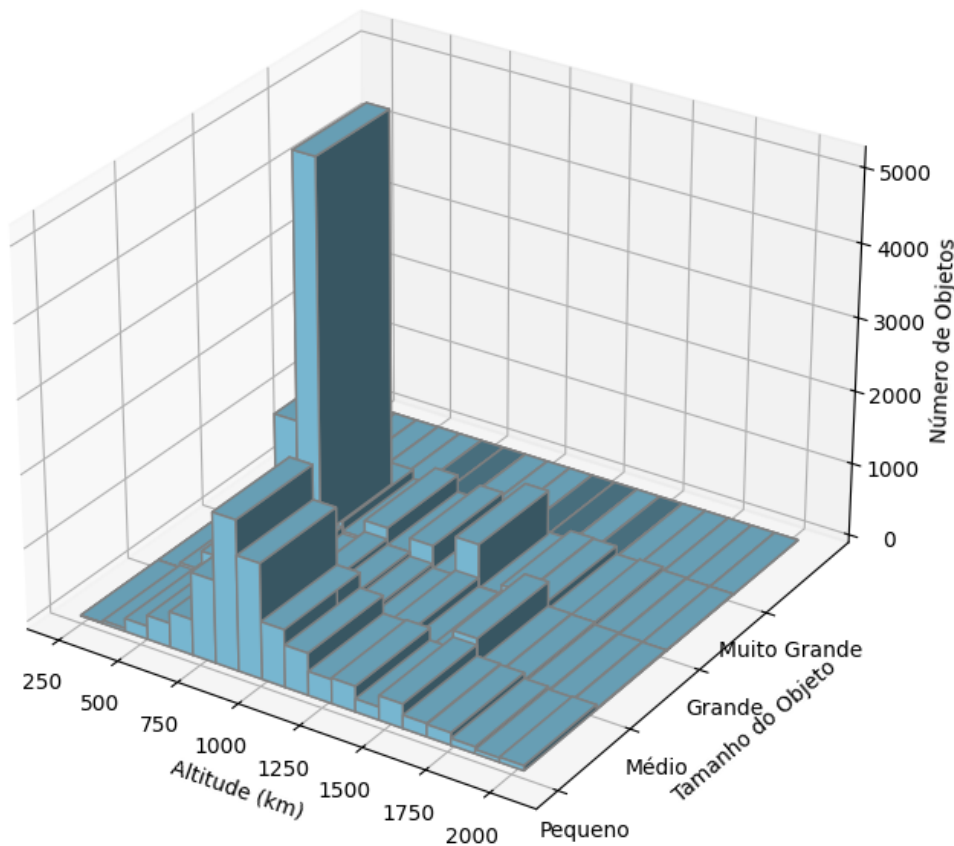


Figure 5.11: Distribution of Objects by altitude and size

5.3 Exploratory Work

This section describes the development of early prototypes with many uses. It serves as an exploration of what was possible to create with the given data. Some objects reflect more on the process than others, but most objects created were experimental.

5.3.1 Tools and Technologies

All the created objects were primarily made in Blender and sometimes directly in Python when the graphic itself was enough to import an STL file. When that was not possible, the coordinates were saved in a CSV file and exported into Blender. Some pieces were made directly in Blender without the need for a CSV file, but with consideration of the images produced in Python. For all the 3D-printed pieces, the slicer used was Bambu Studio [BambuLab, b], and the printing was carried out on a Bambu Lab A1 printer [BambuLab, a]. Some pieces utilized the

AMS, while others were printed separately for later assembly. The filament used was always PLA (Polylactic Acid).

5.3.2 Experiences

Lithophanes

When exploring the first dataset [UNOOSA, 2024], which included only the countries, launches per year, and country code, the countries were grouped by continent, and a bar chart was created (Figure 5.4). Some examples in data physicalization have explored touch using lithophanes [Koone et al., 2022]. These are especially useful for making data more accessible to those who are blind or have low vision by utilizing tactile graphics, physical models, audio, or Braille.

Historically, lithophanes were made from thin porcelain or wax beginning in 17th-century Europe and possibly earlier in China [Carney, 2012]. Inspired by this study, a lithophane was printed (Figure 5.12) that grouped the data. While individuals without visual impairments might think that lithophanes do not show much beyond the graphics displayed on a screen, those with limited vision or who are blind have a more developed sense of touch.

For higher contrast in lithophanes, only black and white colors were used. The main downside to this approach was the readability of the axes and letters. However, since the target audience for this visualization typically does not rely on our standard writing system and prefers elements such as Braille, the axes and letters could have been omitted from the visualization without affecting the final result.

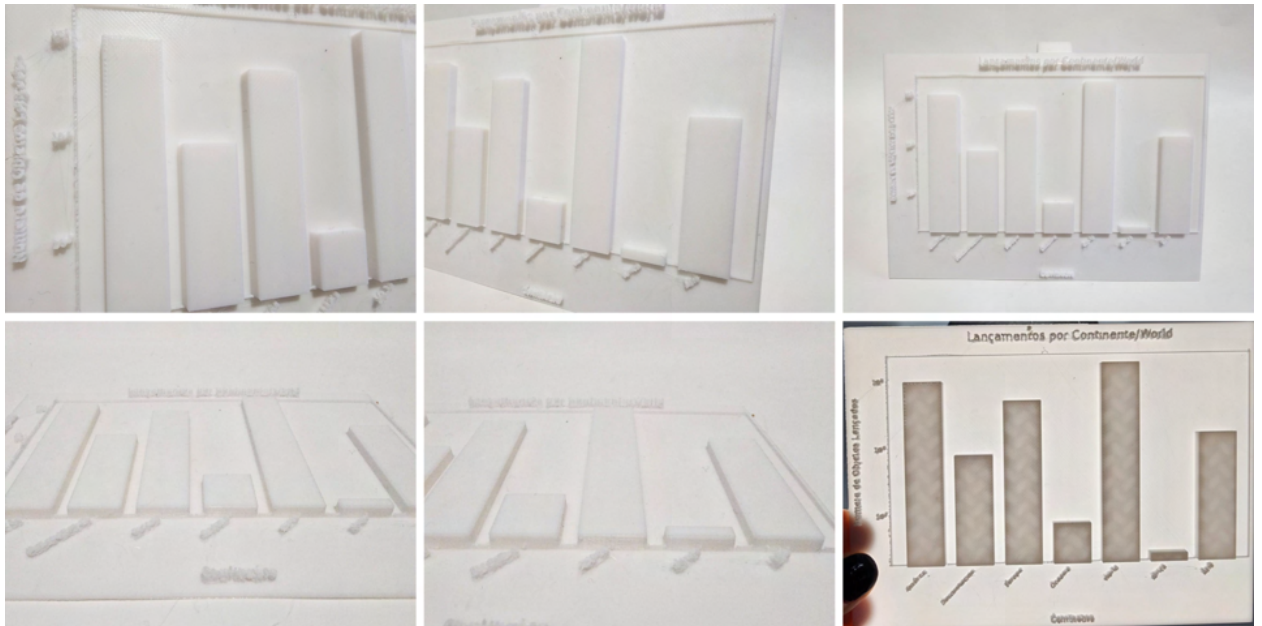


Figure 5.12: Lithophanes of launches per Continent/World

Zoetrope

Using the first dataset [UNOOSA, 2024], the idea of creating a zoetrope to represent the number of objects launched per year over the last 24 years came to life. A 3D graphic was created in Python (Figure 5.5). As previously mentioned, the countries were grouped into continents, and the three continents with the highest number of launches during these years were selected for this graphic. The coordinates of the graphic were exported into a CSV file, which was then imported into Blender.

Each coordinate had an associated cube, and the scale was set according to the data. A few adjustments were necessary to ensure the scale fit the 3D printer. Additionally, a base was created for the bars, and the years were added to the base.

Each continent is represented by a different color: World is yellow, America (including North, Central, and South America) is black, and Europe is pink. The bars also rotate along the circle, completing a 360° turn when they reach the end. This piece was printed in parts, as printing it as a single piece would have been too time-consuming and would have used too much filament. Therefore, the base was printed first, followed by the bars, which were then fitted into the base. Later, the numbers on the base representing the years of launches were painted in red (Figure 5.13).

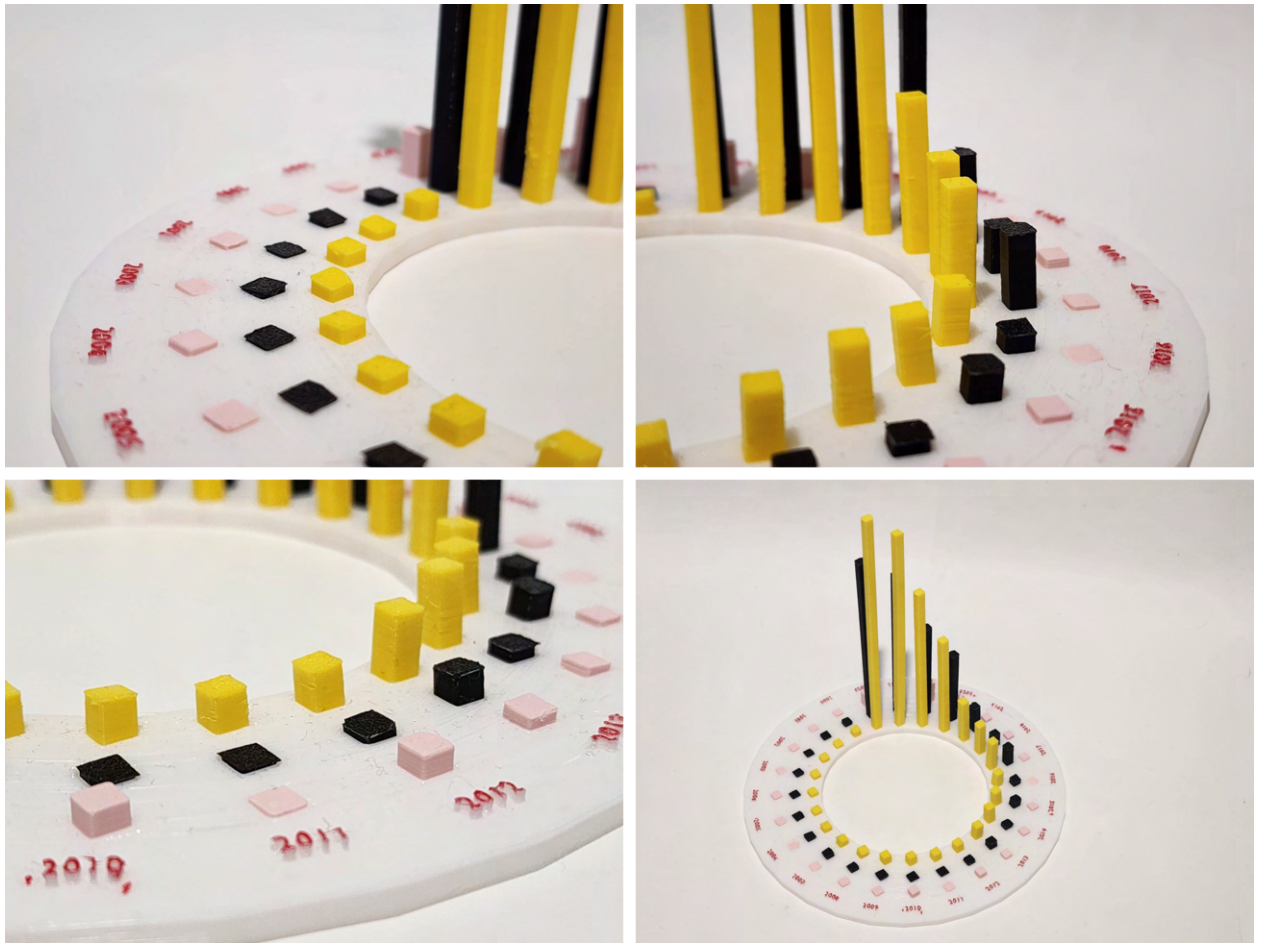


Figure 5.13: Zoetrope without the logarithmic scale

The main goal of this physicalization was to observe how the eye perceives the movement of sudden increases, decreases, and drops and to see if it would be possible to create a zoetrope to represent data, so curiosity was also a big part of it. However, the significant differences in the number of launches disrupted the illusion of the zoetrope. Since a zoetrope is an animation technique that relies on frame-by-frame motion, the significant gaps in the data caused the movement to be lost, making it difficult to perceive the ups and downs, especially the movement.

Another attempt was made using a logarithmic scale (Figure 5.14), which proved to be much more successful in conveying the movement. With the ups and downs closer together and the difference between the first and last years reduced, it was possible to perceive the movement more clearly. A video of this version can be found [here](#), where it was filmed at 15 frames per second.



Figure 5.14: Zoetrope with the logarithmic scale

Bubble Gear Chart

Another experience involved categorizing the different objects in space, which were divided into Debris, Payload (Satellite), Rocket Body, and Unknown in Spacetrack.org dataset. Initially, a bubble chart was created using Python (Figure 5.15). Thinking about how to represent this physically, it was decided that gears would be a good way to depict the objects orbiting Earth since they move, and historically, many representations have used the movement of gears to illustrate

the orbits of planets.

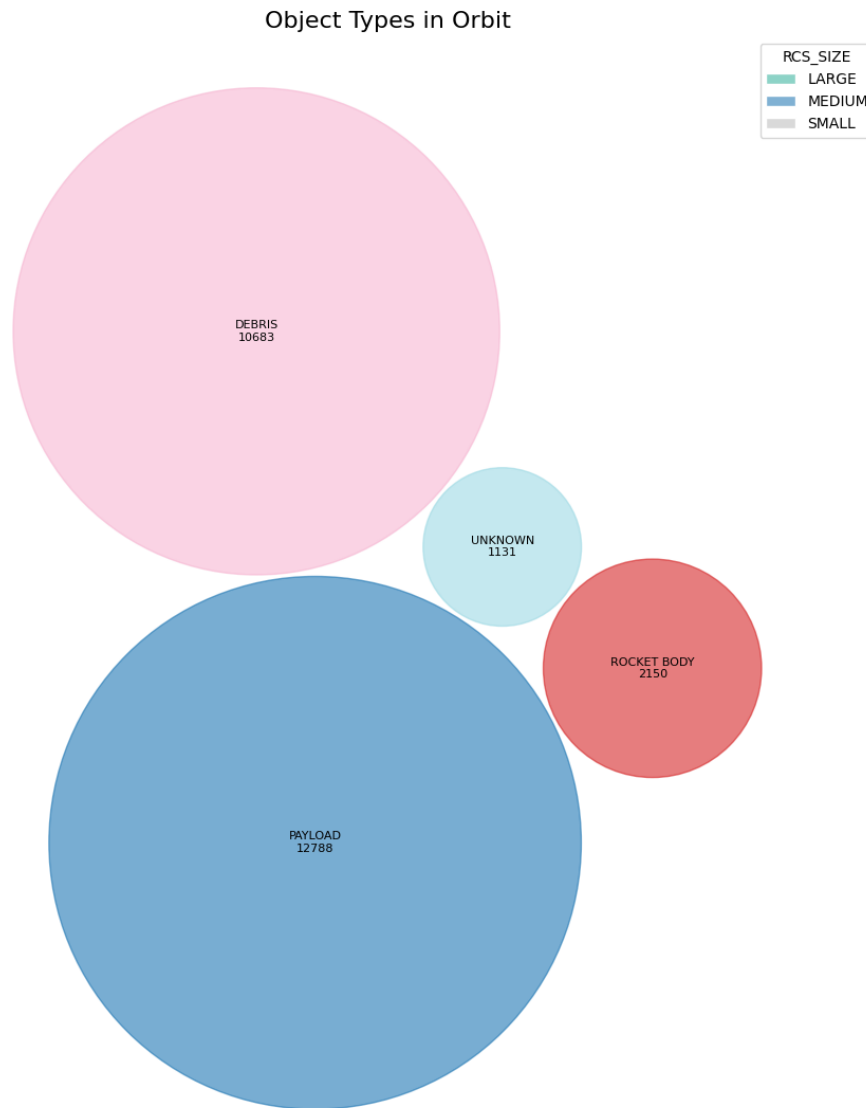


Figure 5.15: Bubble Chart created in Python

With this idea in mind, the image was imported into Blender, and the gears were created. Since there were four different kinds of objects in the dataset, four gears were made, maintaining the aspect ratio of the bubble chart created in Python. Other methods to convey the information, such as varying the number of teeth on each gear, were considered, but they would have been too large and could have obscured the purpose. Therefore, maintaining the area and aspect ratio of the gears was the chosen approach.

To ensure they fit correctly, two gears were always touching each other, but three gears could not touch simultaneously, as this could impede movement. Consequently, two gears rotate clockwise, and the other two rotate counterclockwise.

After the gears were created, the best way to print them was in pieces to save filament and maintain a more modular design. A base was created along with

several pieces to fit the gears into the base (Figure 5.16). After a few tolerance tests, the Bubble Gear chart was printed(Figure 5.18).

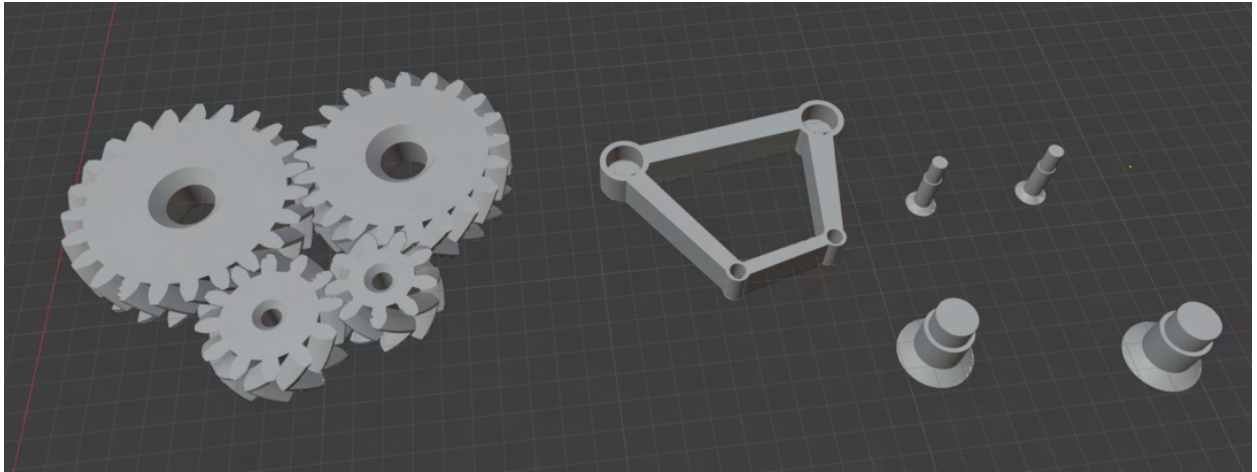


Figure 5.16: Pieces of the object in blender

One of the main analogies for the print was that it is usually difficult to perceive what is orbiting us, such as satellites, rocket bodies, debris, or other objects. On one side, everything is the same color (Figure 5.17), white, but when you turn it over, you can see that many objects compose the piece being represented by different colors, with red being debris, blue satellites, yellow rocket bodies, and green unknown objects. The gears are functional, allowing them to rotate and be manipulated.

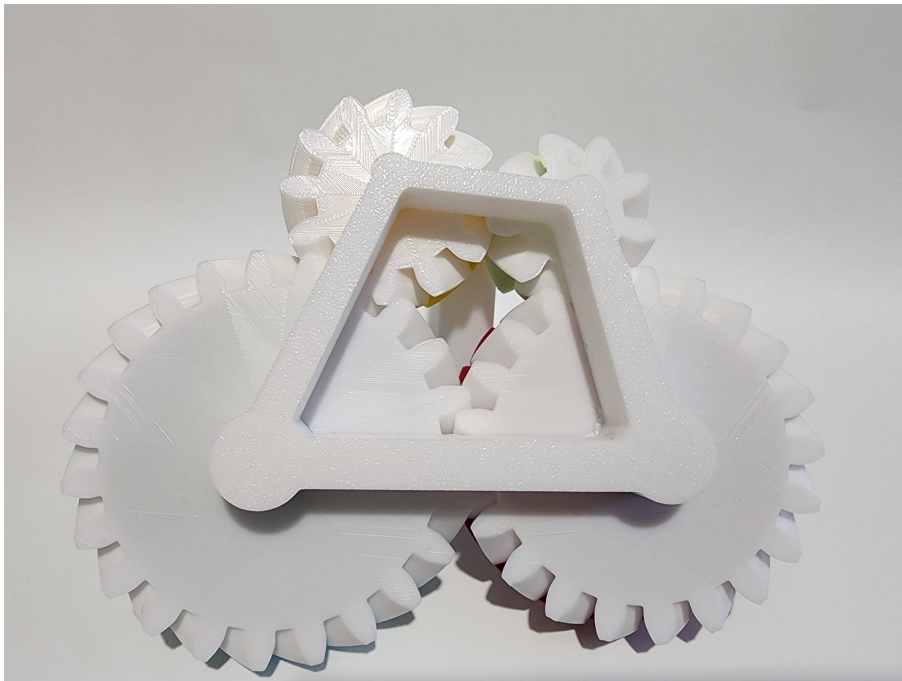


Figure 5.17: Bubble Gear Chart back

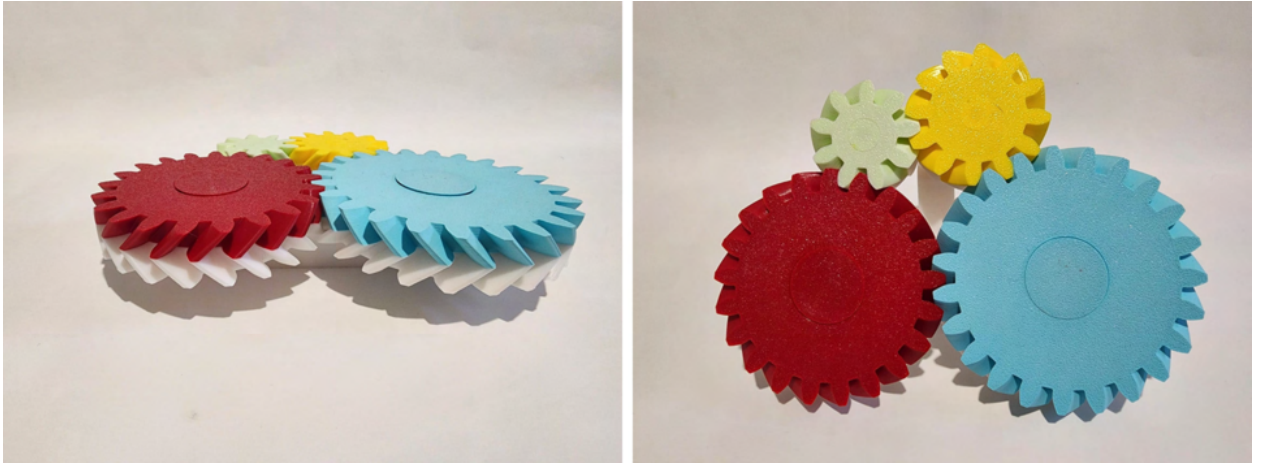


Figure 5.18: Bubble Gear Chart front and side

Data Sculptures

Some data sculptures were created using the data available on SpaceTrack.org [SpaceTrack]. The first one, "Trash Mountain" (Figure 5.19), shows the amount of accumulated objects along the years and is divided into the main orbital regions: LEO, MEO, GEO, and Other.

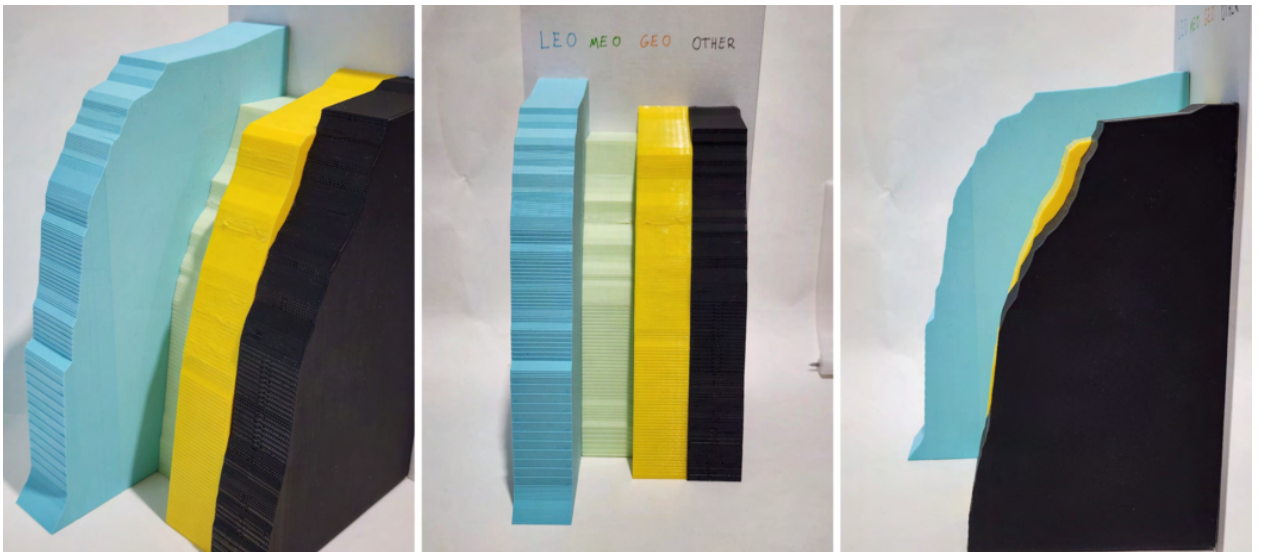


Figure 5.19: Trash Mountain, created by the author

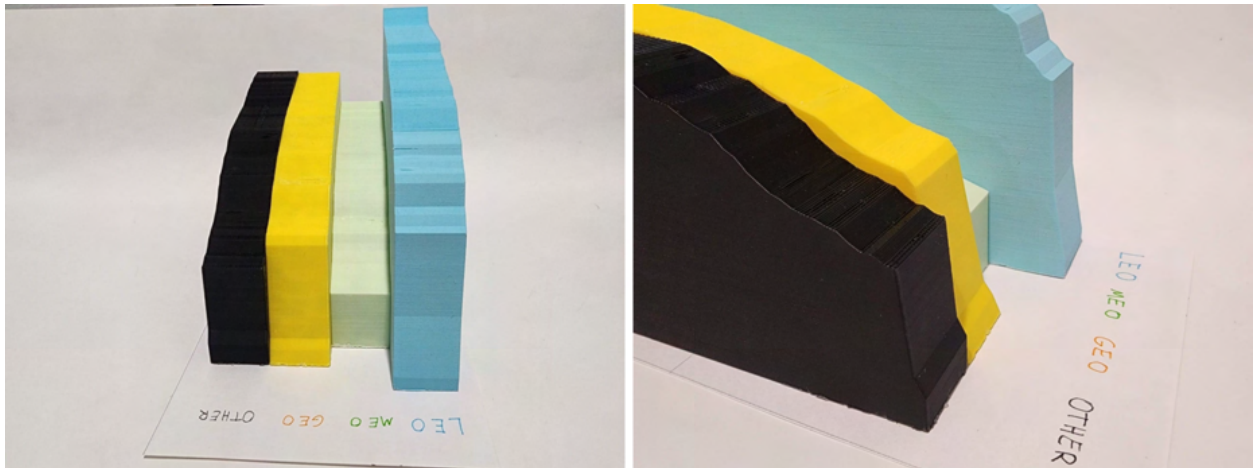


Figure 5.20: Trash Mountain side, created by the author

Since the dataset used makes use of the Two-Line Element (TLE) data and includes the periapsis (the closest point in an object's orbit around Earth) and apoapsis (the farthest point), the average altitude is calculated as the mean of the periapsis and apoapsis. This representative value reflects the general elevation at which the object operates. The average altitude is then used to classify each object into one of the main orbital regions:

- **Low Earth Orbit (LEO):** Objects with an average altitude of 2,000 kilometers (km) or less are categorized as LEO. This region is typically occupied by satellites used for telecommunications, Earth observation, and the International Space Station (ISS).
- **Medium Earth Orbit (MEO):** Objects with an average altitude greater than 2,000 km up to 35,786 km fall into the MEO category. MEO is commonly used for navigation satellites, such as the Global Positioning System (GPS).
- **Geostationary Orbit (GEO):** Objects with an average altitude of more than 35,786 km are classified as GEO. Satellites in this region maintain a fixed position relative to the Earth's surface, making it ideal for certain communications and weather monitoring satellites.
- **Other:** Orbits that do not fit into the above categories, such as high elliptical orbits, sun-synchronous orbits, or polar orbits.

The number of objects in each region was grouped by category and plotted by year, creating a simple line chart from the first year a satellite was launched to the last day data was available. A logarithmic scale was necessary to better visualize the differences, as the disparity between the LEO region and the others was too significant to ignore. After the graphics were created, they were exported in SVG format and imported into Blender, where the sculpture was modeled and printed. Each region is represented by a different filament color. The goal of this visualization was to create a sculpture that illustrates the accumulation of objects over time, resembling a mountain of piled trash.

Seeking to explore additional relationships in the data that were not related to time, other sculptures were created. The initial goal was to examine the relationship between the sizes of objects and their quantities at different altitudes. Since the most critical altitudes were for objects orbiting Earth between 200 and 2,000 kilometers, basically within the LEO region, these altitudes were analyzed. Both the altitudes and sizes were binned, resulting in a 3D chart (Figure 5.11).

The graphic was then exported as an STL file, requiring no further modification in any 3D software. The only adjustments made were dividing by region and assigning colors within the slicer itself. The primary objective was to create some sort of tactile map (Figure 5.21) that allows viewers to discern and feel which object sizes are more concentrated at specific altitudes. The markings were then hand-drawn on a piece of paper.

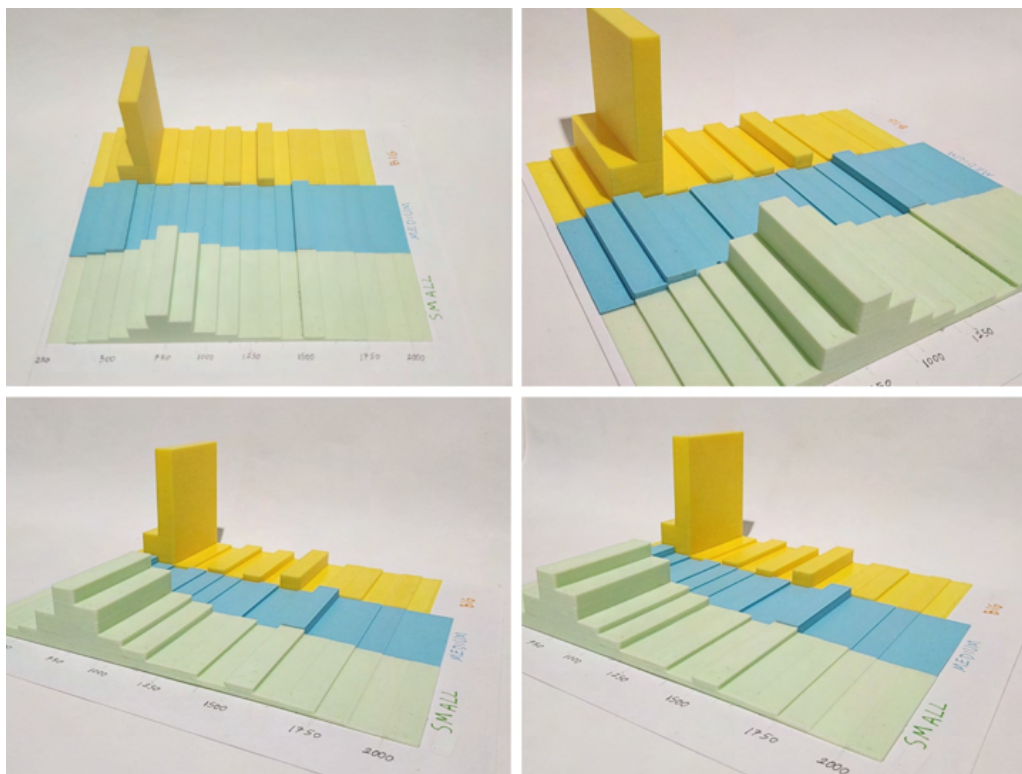


Figure 5.21: Tactile Map of Objects in LEO orbit

Another tactile map, similar to the one above, was created using only objects representing debris (Figure 5.22) to illustrate the amount of debris in the LEO region. A logarithmic scale was necessary because the number of small objects was significantly higher than that of larger or medium ones. The map was printed in the same manner as the previous one, with different colors representing different sizes of objects. As seen, most debris is situated at lower altitudes, with smaller objects being more prevalent, while medium and larger ones are less common.

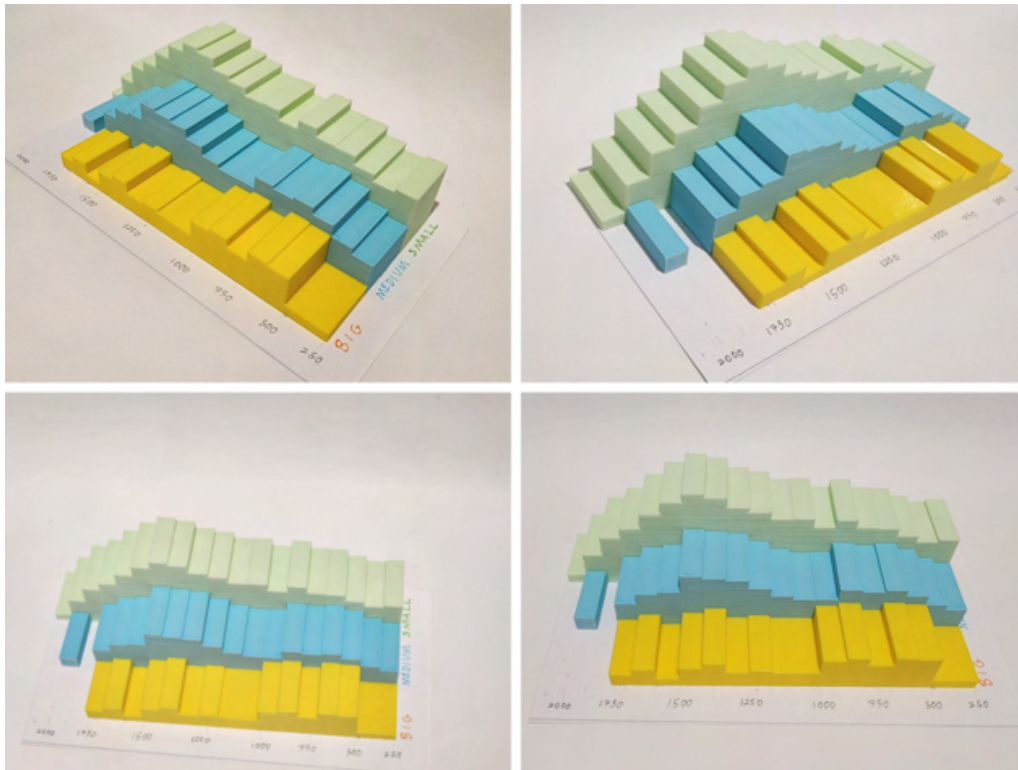


Figure 5.22: Tactile Map of Debris in LEO orbit

Bracelets

A new idea emerged after some analysis using the dataset from SpaceTrack.org [SpaceTrack]. Considering that objects orbiting the Earth are usually not visible to the public, the issue remains an invisible problem that some people may hear about and proceed with their lives. The main concern is that if a collision happens, the multitude of elements involved can lead to an extremely chaotic scenario. This phenomenon is known as the Kessler Syndrome [Kessler et al., 2010], where a single collision can generate a cascade of collisions, increasing exponentially the amount of debris, this can make Earth's orbit unpredictable and dangerous, threatening the functionality of satellites and the safety of future space missions.

Most people do not think about what would happen if satellites collide, but these events can have profound consequences. Collisions can disable or destroy active satellites, leading to the loss of services like global positioning systems (GPS), telecommunications, weather forecasting, and Earth observation [Nozawa et al., 2023]. The debris generated from these collisions would continue to threaten both existing and future satellites, increasing the likelihood of more collisions and complicating space operations.

The economic impact of losing some essential satellite services and the costs associated with debris mitigation and removal efforts can also be too much for the economy. [Nozawa et al., 2023].

Addressing this problem is crucial, yet the general public remains largely un-

aware. To bridge this awareness gap, one of the ideas was to create something wearable that people could incorporate into their daily lives. A bracelet was chosen as the medium because it is an everyday accessory, often worn alongside devices like smartphones. By designing a bracelet that represents the thousands of satellites above us, the public would be able to physically feel the weight of the consequences that lie in space. Using it in the same hand of a device we all use to communicate, our phones, emphasizing that our connectivity depends on the infrastructure at risk if the Kessler Syndrome scenario unfolds.

The initial design focused on creating a radial chart with the accumulated number of objects launched each year. Each bracelet represents one year, incorporating the number of launches that year. This was later visualized in Python using "spikes," where larger spikes indicate more launches. Over the years, the number of spikes increases significantly, from just a few in the early bracelets to large, almost complete coverage in the final years (Figure 5.23).

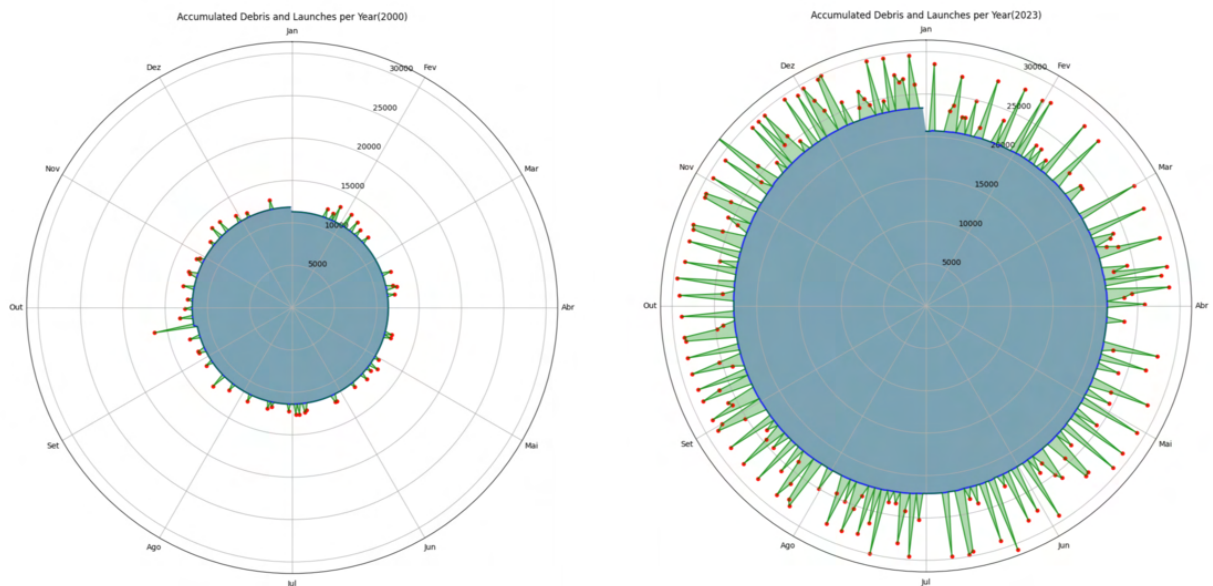


Figure 5.23: Graphics for the bracelet

The bracelet uses two different scales: a linear scale for the total launched objects and a logarithmic scale for launches per day for better visibility of the launches. The radius of the bracelet and the size of the spikes increase over the years, covering data from 2000 to 2024. It is important to note that the 2024 bracelet is incomplete since the dataset was acquired in mid-November, so some launch data for that year are missing since it was not over yet. All graphics were created in Python, exported to Blender, and converted into meshes. The holes in the bracelets remain consistent, the only variations are the number of spikes and the expanding radius over the years.

The mass of the bracelets were also considered to represent the weight of space debris accurately. A simple calculation was made to scale the infill percentage based on the number of objects launched each year. The maximum infill for the year 2024 was set at 98%, with other years proportionally scaled according to their launch counts:

$$\text{Infill} = \left(\frac{\text{Total Accumulated by Year} - \text{Total Accumulated by 2000}}{\text{Total Accumulated by 2024} - \text{Total Accumulated by 2000}} \right) \times 98\%$$

Table 5.2: Infill and Weight in Grams for 3D Printing

Year	Infill (%)	Weight (grams)
2000	0.00	3.99
2001	0.80	4.85
2002	2.04	5.34
2003	2.78	6.05
2004	3.47	6.50
2005	4.09	6.68
2006	5.10	6.91
2007	6.04	7.35
2008	7.50	7.81
2009	8.48	9.25
2010	9.97	9.42
2011	11.65	9.81
2012	12.90	11.26
2013	14.46	11.80
2014	16.83	13.08
2015	18.09	14.57
2016	19.26	15.17
2017	20.67	16.01
2018	23.70	17.67
2019	25.50	19.45
2020	31.37	24.06
2021	41.17	33.91
2022	60.11	51.29
2023	78.98	93.51
2024	98.00	134.30

The filament chosen to represent the bracelets was transparent PLA, symbolizing the invisible nature of the space debris problem that needs to be addressed (Figure A.4).

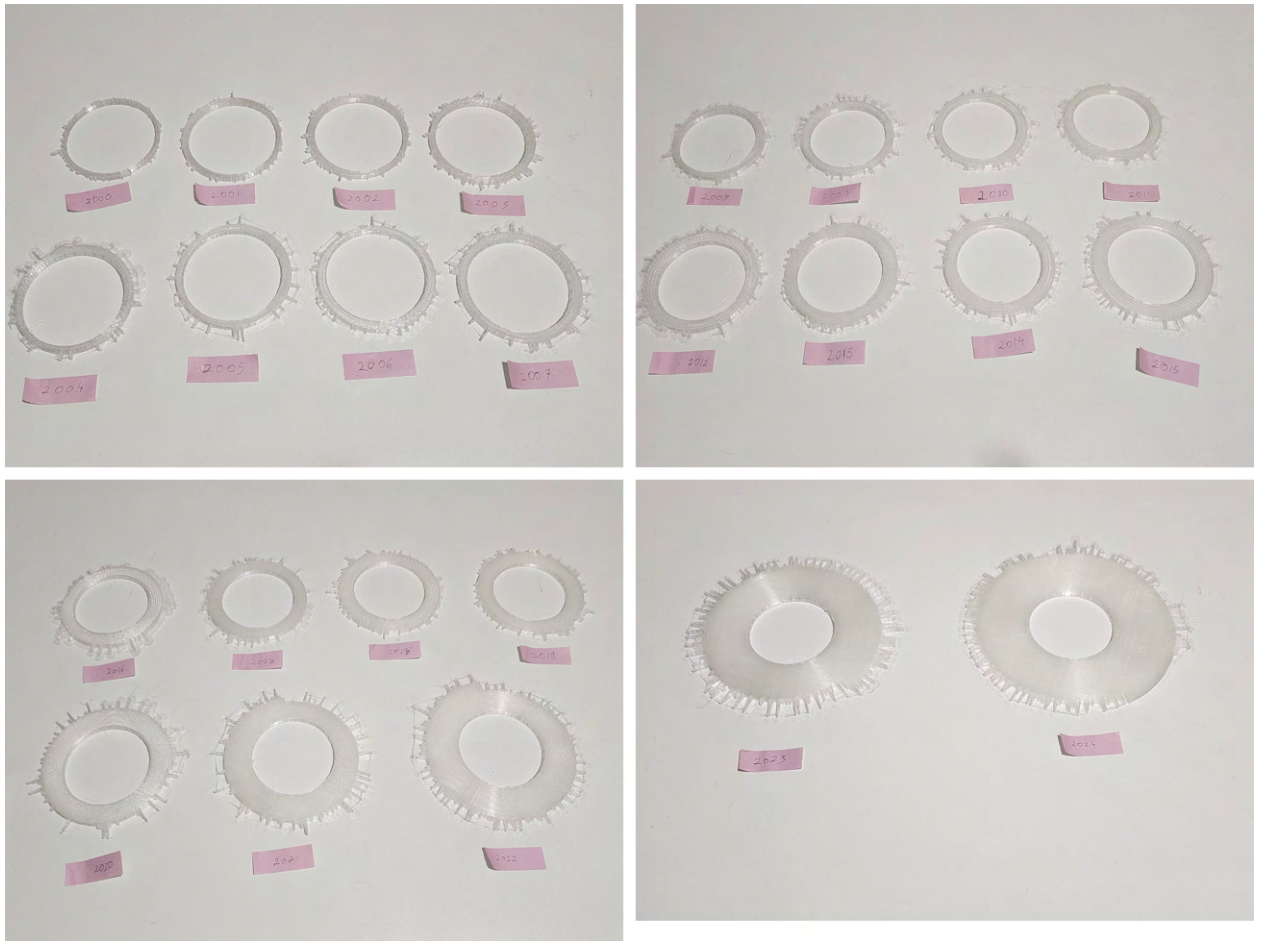


Figure 5.24: Bracelets from 2000 to 2024

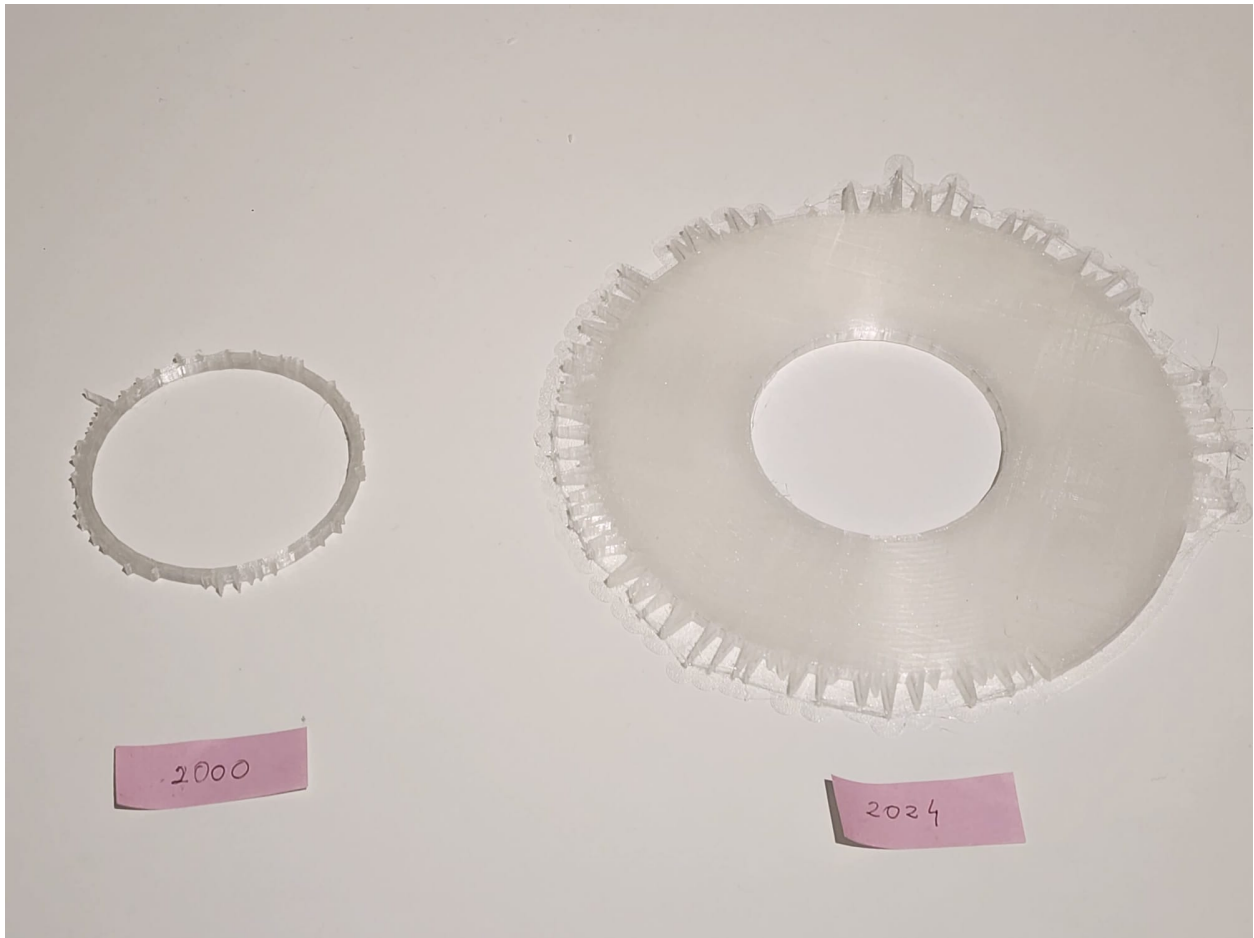


Figure 5.25: Comparison of the first bracelet (2000) and the final bracelet (2024)

5.4 Discussion

Many of the physicalizations created are indeed interesting, but they often emerged from a simple desire to explore the dataset and test how certain aspects might be represented. Consequently, some feel quite limited, some are basically 2D charts turned 3D, slightly more tactile but not adding genuine new insights. One idea we found most promising involved gears, yet they never really fulfilled their full potential, they were used more as a playful mechanism than as a means of encoding additional information, so it ended up being more of a glorified bubble chart. The same way, the “mountains of trash” were basically just 2D line charts that got 3D-printed.

That said, this phase was necessary to understand what was possible with data physicalization and a 3D printer, this was an exploration phase. For the next steps, we want to go deeper. We intend to be more deliberate about how we visualize and explore the data, paying close attention to the metaphor, imagery, and interactions we want to convey to the public.

The goal is to create something more meaningful, where the mechanical elements, if used, genuinely serve to communicate or enhance the data, and where the tan-

gible aspect brings a richer dimension. By focusing on metaphor, design, and user interaction, we hope to produce a data physicalization that is not only visually compelling but also truly meaningful in how it conveys information.

Chapter 6

Design Iterations and Final Object

Many design iterations were conducted throughout the project. After conducting the preliminary experiments, we revisited the datasets and reanalyzed the information to gain a deeper understanding of how different aspects could be effectively conveyed through physical form. One of the challenges of working with space debris is the large amount of data available, and not all of it contributes equally to the intended message. Since the campaign's goal was to raise awareness, the design decisions had to prioritize clarity and impact.

The datasets contain multiple dimensions, including object type, mass, speed, launch date, orbit height, country of origin, and more. From these, we selected three main narratives to communicate.

The first aspect focuses on how the number of space objects has grown over time. Each year, an increasing number of objects are launched, and this growth is not linear. The second aspect highlights the total accumulation of objects currently orbiting Earth, including inactive satellites and debris that continue to pose risks. The third aspect addresses the speed at which these objects travel, where even small fragments can move fast enough to cause catastrophic damage. These aspects were chosen because they can better illustrate the scale, permanence, and physical danger of the issue at hand.

Most of the physical artifacts created during the project were designed to communicate one of these aspects. While not all of them could be entirely fabricated due to technical and material limitations, their conceptualization and partial implementation contributed to the overall exploration. The design of the final sculpture, as well as the other prototypes, forms a campaign where each object targets a different dimension of the problem.

In the following sections, each prototype is presented along with its objective, data mapping, visual language, and fabrication approach. The section concludes with the final object, a sculptural representation inspired by the notion of a "trash mountain," symbolizing the cumulative growth of orbital debris over decades.

6.1 Motion Test Zoetrope

One of the early and more playful experiments was a data-driven zoetrope. The initial concept was a circular bar chart designed to spin, creating a dynamic visualization. While visually engaging, the movement did not add any significant value to the legibility of the data, it served more as a novelty than a precise representational method. The form presented limitations in how effectively it could convey detailed information.

Further research led to the work of Retchy [Retchy], who developed many exploratory zoetropes that pushed the medium in an experimental direction, creating a range of different movements. A particular version of interest was designed in the shape of a dome. Inspired by this approach, we aimed to reproduce a similar form to explore whether this type of motion could be effectively adapted to the presented data.

A prototype dome was constructed using papier-mâché and placed on a rotating platform to simulate the movement (Figure 6.1). The video of the object moving can be checked [here](#). Although the result was visually interesting, it became evident that incorporating large volumes of data into this medium would not give any readable or informative outcomes. While such a format may work well for representing small-scale or periodic datasets, in this case, it lacked the accuracy and clarity necessary to effectively communicate the satellite data. For these reasons, the concept was ultimately discarded.



Figure 6.1: Dome zoetrope Prototype

The intention was to represent the growth of satellite constellations using a dome

structure. However, this proved to be technically unfeasible. The complexity of encoding the volume and temporal distribution of constellation data on a three-dimensional, rotating surface was not compatible with the resolution required. The amount of data and the limitations of physical motion would have compromised the integrity of the information.

6.2 Orbital Debris Iris

The goal of the Orbital Debris Iris was to create a kinetic piece whose diameter would expand or contract according to the number of objects launched in a given year. In practice, each ring would exist on its scale, allowing the viewer to perceive the acceleration of launches as a live dataset rather than a static bar.

6.2.1 Mechanised Prototype

During the mechanical survey, we encountered a planar, radially deployable scissor linkage patented by Chuck Hoberman in 1991 [Hoberman, 1991]. The device, known as a Hoberman ring, consists of two concentric rings of identical scissor pairs that slide over one another, allowing the entire circumference to expand and collapse while the center remains stationary. The linkage matched both our functional needs and the visual language.

We initially attempted to model the kinematic system from scratch, but then discovered a Fusion 360 file [YonatonKaufman] and produced a first PLA prototype. There were a few issues with the first print. Tolerances were tight, most joints required manual reaming with a modeling knife, and the high friction meant the ring could only be opened or closed by applying considerable force. A thin coat of silicone grease on every pivot reduced friction and allowed for a smoother actuation, as a significant amount of force was required to open or close the structure before applying the grease. (Figure 6.2)

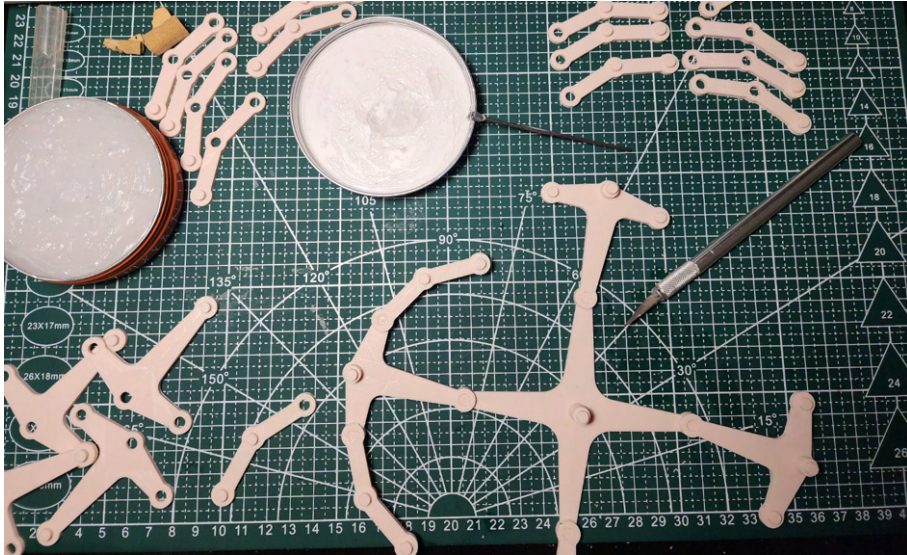


Figure 6.2: Post Processing

Another problem that showed up quite early was the lack of bevels in the model. Some of the linkage bars were crashing into each other when we tried to close the ring (Figure 6.3), so to completely close the structure we had to stop, lift the whole object slightly upward, pull it, and even then it still refused to retract completely.

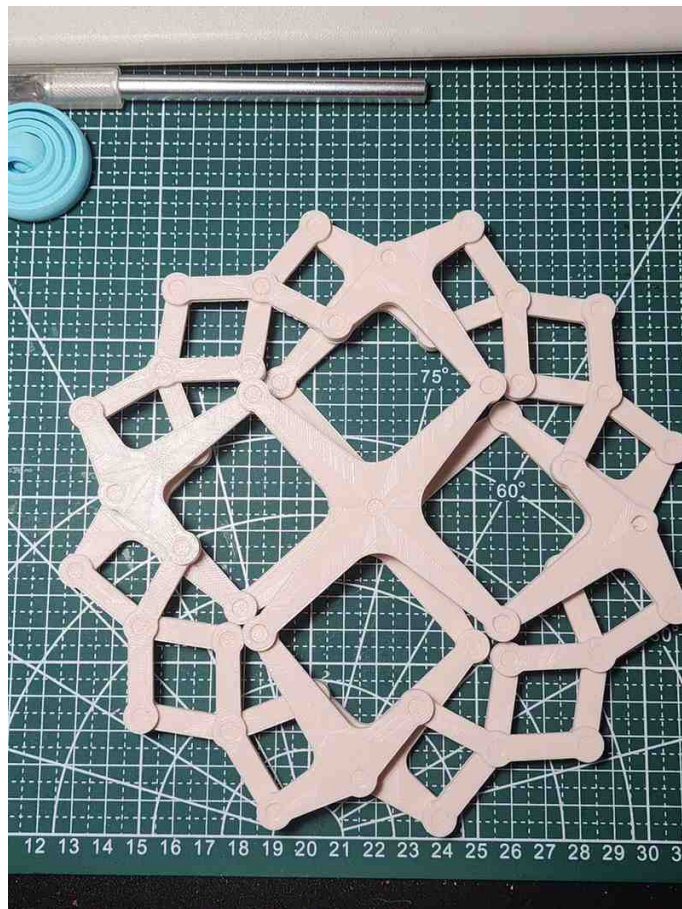


Figure 6.3: Bevels

To solve this, we first identified the exact collision points and then added small bevels (Figure 6.4) to those spots to provide the bars with a smoother path.

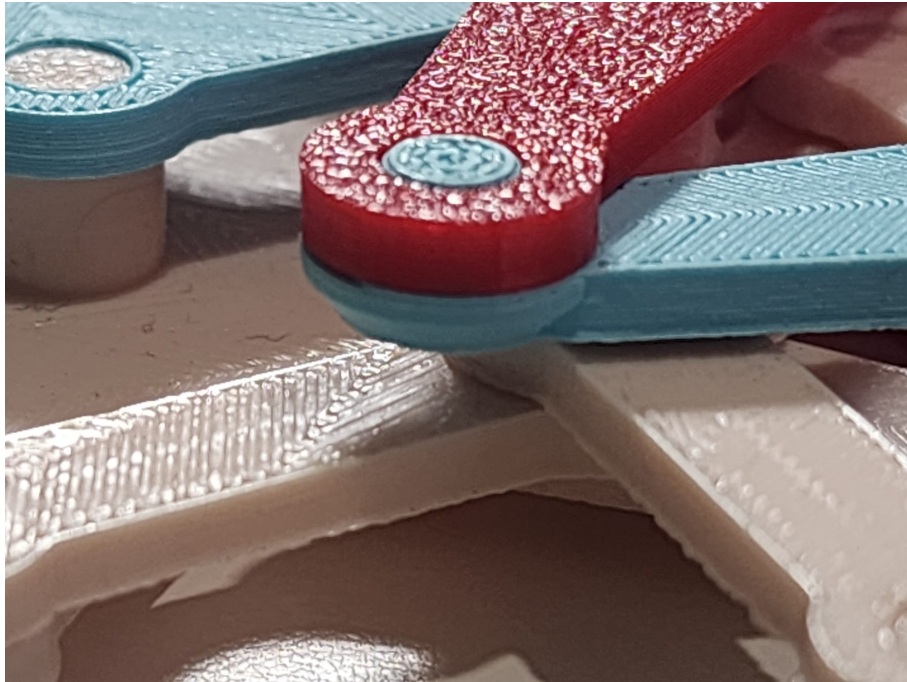


Figure 6.4: Bevels

We printed the new parts, reassembled everything, and applied the same layer of silicone grease to the joints. After that, the iris could finally open and close by hand without getting stuck. (Figure 6.5)

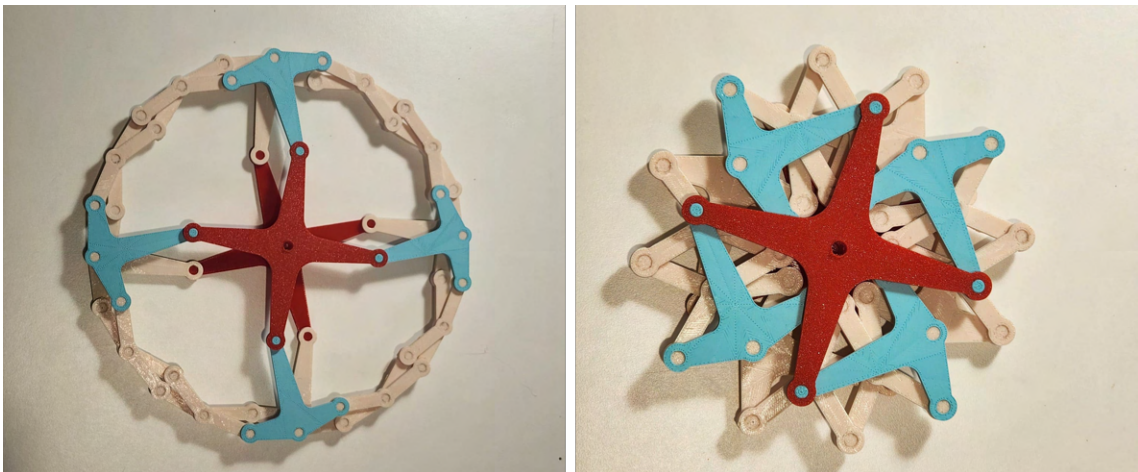


Figure 6.5: Mechanism opening and closing

With the manual motion working, we proceeded to integrate the motor. We modified the central plate to accommodate a 5 V stepper motor within the hub. However, during the first test run, the shaft of the motor spun freely while the structure remained stationary, meaning the torque was being applied only to the motor, not to the ring. To solve this, we redesigned the hole, creating a tight D-flat

profile so that the shaft would lock securely to the hub. This eliminated the slipping issue, but the small stepper still lacked sufficient torque to overcome the friction generated by all sixteen PLA hinges.

Because a Hoberman-type ring[Hoberman, 1991] expands by pulling the opposite sides at once, we considered two options:

1. Building a rigid C frame that connects both halves
2. Creating a precise bore in the hub so the motor shaft itself pushes and pulls symmetrically.

The first option would have blocked part of the expanding mechanism, so we opted for the second. We measured the shaft, remodelled the hub, printed the new part, and tested again. The shaft no longer slipped, but the 5V motor still didn't move. We concluded that we would need either a stronger motor or lighter, lower-friction joints, and both were outside our current time and budget.

6.2.2 Model and Rendering

For this reason, the physical build stops at the hand-actuated stage, and the effect of yearly expansion and contraction is shown only in the 3-D renders (Figure 6.6).

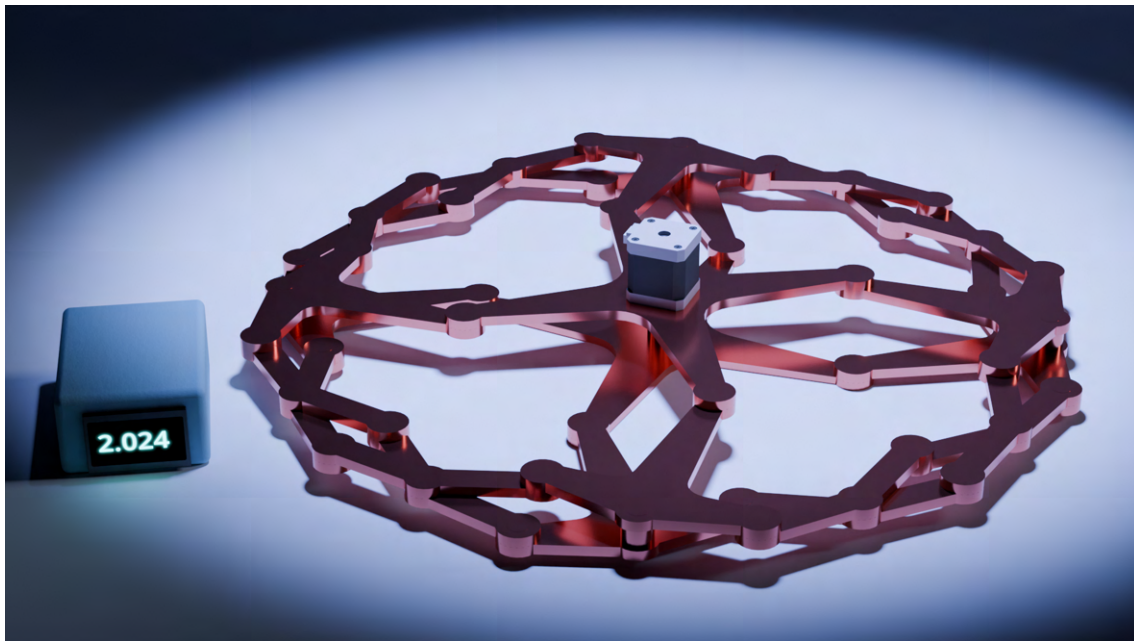


Figure 6.6: Render of the Orbital Debris Iris

To decide how much the Orbital Debris Iris should open each time, we first quantified the launches by decade.

The chart in Figure 6.7 shows that each bubble represents a decade, and its label reports the exact number of satellites launched. Working decade-by-decade

keeps the story more readable and manageable, an annual ring for every year after 1957 would require over 70 discrete steps, far beyond the practical resolution of a physical mechanism.

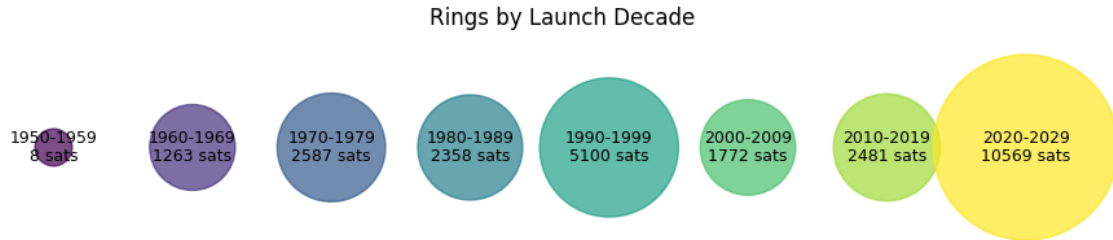


Figure 6.7: Rings by Launch Decade

The printed test ring measures 14 cm in diameter when fully closed and 22 cm when fully open, giving an $\Delta D = 8\text{cm}$.

For the exhibition version, we plan a larger mechanism that tops out at 50 cm. Mapping the normalised radius $r_{\text{norm}} \in [0, 1]$ to a physical diameter D follows

$$D = D_{\min} + r_{\text{norm}} (D_{\max} - D_{\min}), \quad D_{\min} = 10 \text{ cm}, \quad D_{\max} = 50 \text{ cm}.$$

Table 6.1 lists the resulting targets. The 1950s ring open at a max of 10 cm, whereas the 2020s decade drives the linkage to 50 cm.

Table 6.1: Diameter for the *Orbital Debris Iris* with a 10–50 cm span.

Decade	Satellites	r_{norm}	Target D (cm)
1950–1959	8	0.00	10.00
1960–1969	1 263	0.23	23.09
1970–1979	2 587	0.46	29.22
1980–1989	2 358	0.42	28.30
1990–1999	5 100	0.73	37.44
2000–2009	1 772	0.33	25.71
2010–2019	2 481	0.44	28.80
2020–2029	10 569	1.00	50.00

For measurement purposes, a few renders with a scale were made to show how the different sizes would look like in comparison with each other (Figure 6.8)

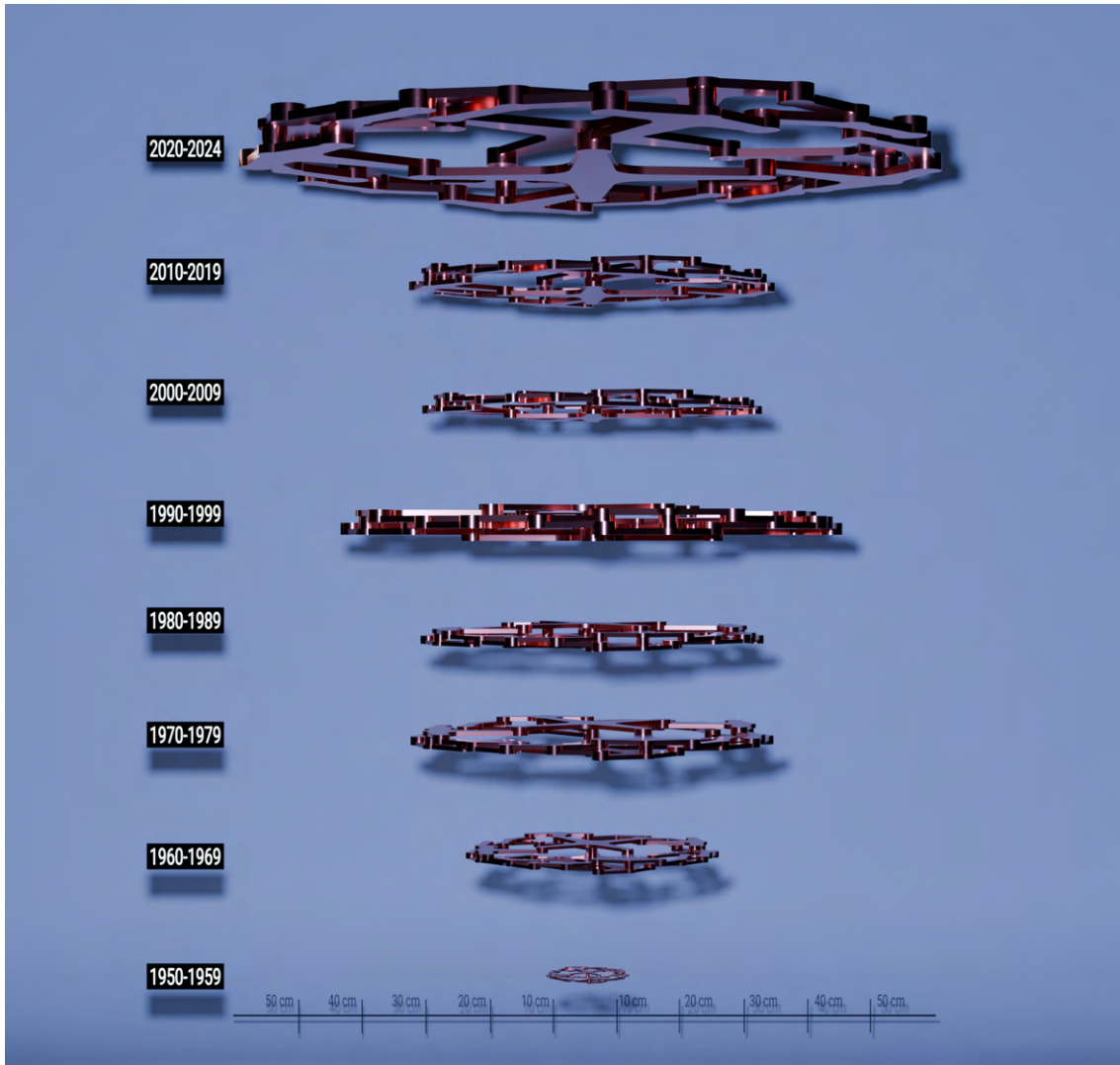


Figure 6.8: Comparison among different scales for the rings by decades.

For the render setup, the main challenges arose in the animation, which is not a trivial task to accomplish. Therefore, we focused initially on the material settings, node configurations, and lighting. The gears in the render were assigned as a metallic material rather than PLA, since PLA was only used in the physical prototypes that revealed the motor's torque limitations.

Being a 3D render, lighting was also taken into consideration. Several point lights were tested to determine the most effective way to highlight the material's surface details and scale. For the material, a Principled BSDF shader was used to mimic metallic properties (Figure 6.9), combined with a subtle color ramp to introduce realistic imperfections (Figure 6.10).

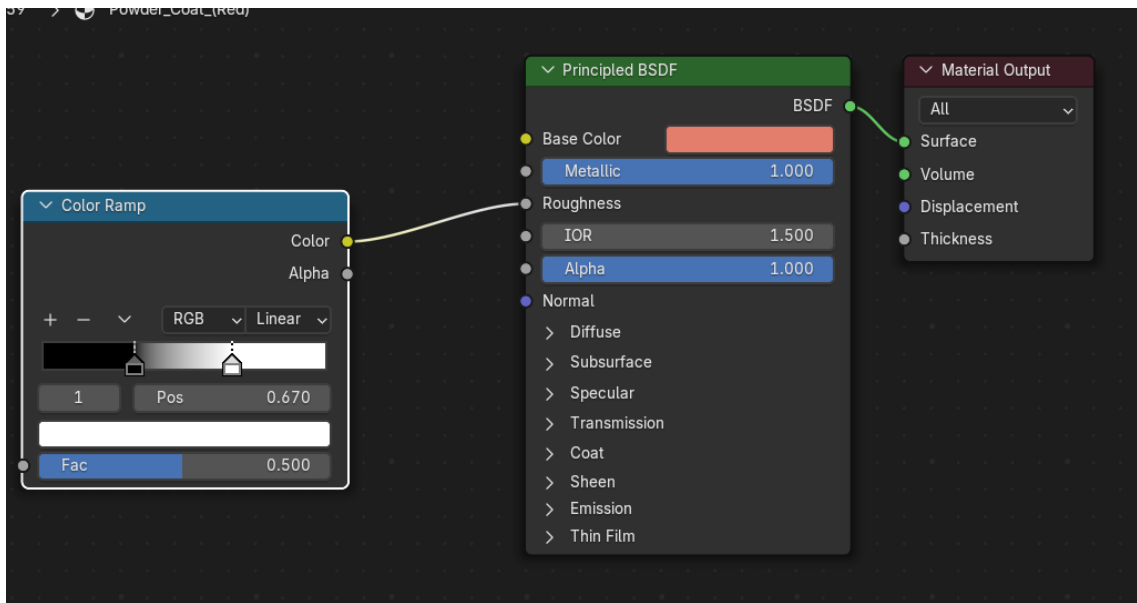


Figure 6.9: Material Nodes

Once the material nodes were finalised, the attention shifted to the lighting. Initially, a conventional lighting approach was tested, but experimenting with different color temperatures produced a more visually appealing results. Warmer tones helped emphasize the depth and texture of the metallic surface, while cooler temperatures enhanced the contrast between the gears and the background. To balance realism with visual clarity, the final setup employed a three-point lighting scheme, supplemented with low-intensity fills to soften shadows. This ensured that the structural details remained visible even in motion.

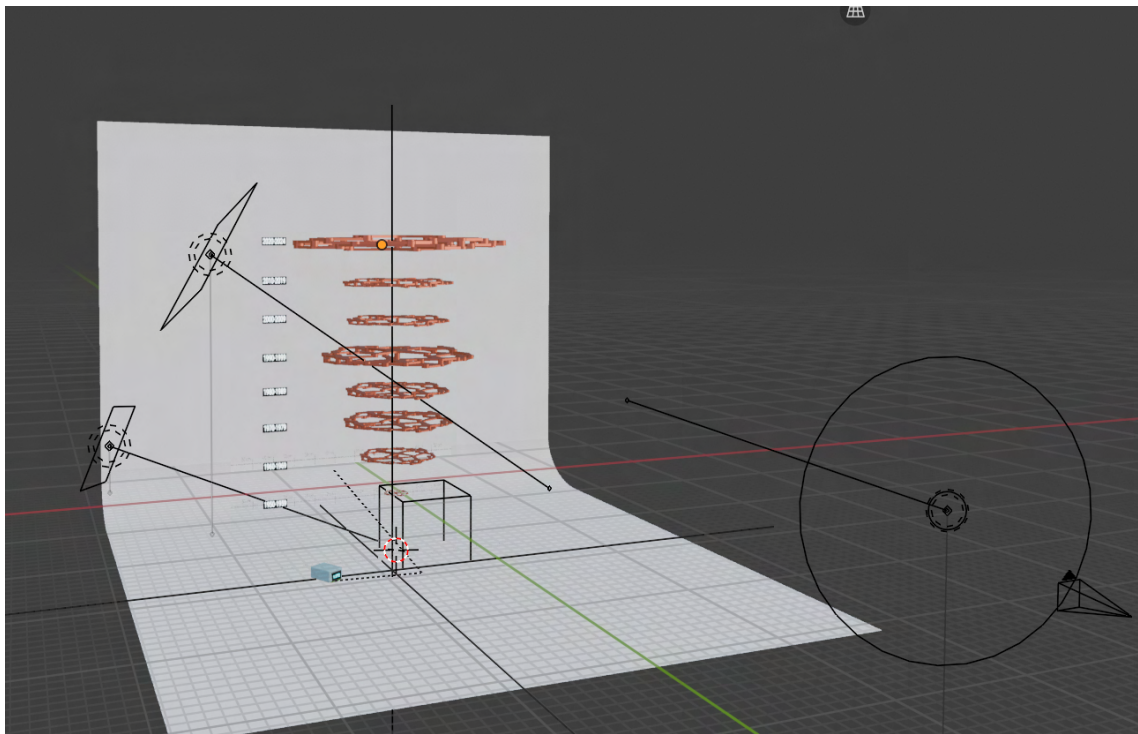


Figure 6.10: Lighting Setup

6.3 Speed Track

Another experience was the bubble-gear one (Page 78). Inspired by this idea, we tried to see what could be represented through the motion of the gears and how those motions could encode data.

Gear mechanisms are fascinating, but they also pose a challenge to represent: it is difficult to show what the gears are doing, especially when the goal is to present data. In our survey, we could not find prior work that uses gears explicitly as a data-representation device.

Delving deeper into the subject, we realised that there are many ways to catalogue mechanical movements. One famous example is the Engineers' Illustrated Thesaurus [Herkimer, 1952], which catalogues hundreds of mechanisms widely used in industrial design. However, differentiating movements produced by reciprocating mechanisms, such as a crank, planetary gears, or the Scotch yoke, is not trivial when what is seen is only a stick going up and down. Plotting the motion as amplitude versus time can reveal more meaningful differences between these movements.

The equation for displacement x as a function of time t in harmonic motion is written as

$$x(t) = A \sin(\omega t + \phi), \quad (6.1)$$

where

A is the amplitude;

ω is the angular frequency;

ϕ is the phase constant, which has the initial condition at $t = 0$.

Many instruments explore this principle. A well-known example is the seismograph, which uses a moving paper roll and a stationary mass to trace vibrations. Electrocardiographs, ink recorders, and strip-chart plotters also achieve a similar "data-on-paper" effect.

On our research we stumbled across *Maker's Muse* video [Angus, 2024], which uses fluorescent vinyl to create traces that slowly fade, allowing for reuse of the material without wasting paper. It also gives the ephemeral aesthetic we wanted: a representation that appears, conveys data, and vanishes. With this representation, we asked ourselves: *Can we make orbital speed visible?*. A key aspect of the awareness campaign is that speeds in space can be incredibly high, especially for small fragments of debris. Even tiny objects, when traveling at several kilometers per second, can cause irreparable damage.

The vertical motion written by each lane is a simple harmonic motion. For an object type j (such as Debris and Payload), the LED mounted on a rotating disc of radius R_j moves as

$$y_j(t) = R_j \sin(\omega_j t + \phi_j), \quad (6.2)$$

The viewer would see a combination of the amplitude and the wavelength.

So the lane with the tallest and most spaced out wave corresponds to the object type with the longest average period. The movement depends on the transport speed of the vinyl, the speed information is given in the scale of the wave, as determined by its orbital period. The calculations related to the math of the information represented on the vinyl can be found in the Appendices.

In practice, the strip of fluorescent vinyl is a set of independent sine waves, one per object type. A larger gear writes a taller, more spaced curve, visually, this means that the highest, broadest wave on the vinyl belongs to the slowest object type in that orbital band, while the flattest, tightest wave represents the faster-moving debris. The information lies in the overall size of each gear and in the spacing it writes, making it possible for the viewer to read the hierarchy at a glance: higher peaks mean longer laps around Earth and lower kilometres per second. It is a translation of the movement, although the speed is not directly represented on the vinyl itself, it can be inferred from the different waves being plotted.

Having decided what would be plotted, we delved into the dataset to see how each object type behaves concerning its orbital period by orbital region. So, to perceive how each proportion behaved, we first normalised the object-types to produce a stable set of aggregation and used the given semi-major axis a and eccentricity e , the altitude is h (Eq. 6.3) and the apogee altitude h_{apo} (Eq. 6.4):

$$h = a - R_{\oplus} \quad (6.3)$$

$$h_{\text{apo}} = a(1 + e) - R_{\oplus} \quad (6.4)$$

Each record is classified into one of four bins:

- LEO: $h \leq 2\,000$ km
- MEO: $2\,000 < h < 35\,786$ km
- GEO: $|h - 35\,786| \leq 100$ km
- HEO: $h \geq 35\,786$ km or $h_{\text{apo}} > 35\,786$ km

The dataset entries with missing or implausible numbers are discarded.

Inside every orbital region, the periods are grouped by object type and averaged, the average period $\bar{P}$ is mapped linearly to an area A (Eq. 6.5) and converted to a radius r (Eq. 6.6). Then the bubble chart is created.

$$A \leq 3\,000 \text{ px}^2 \quad (6.5)$$

$$r = \sqrt{\frac{A}{\pi}} \quad (6.6)$$

For each of the four regions the layout is rendered using a Python library *matplotlib*, creating comparison bubble charts for each orbital region, LEO (Low Earth Orbit), MEO (Medium Earth Orbit), GEO (Geocentric Earth Orbit) HEO (High Earth Orbit) and general, taking the speeds of all orbital regions and directly comparing them without taking in account the orbital region (Figure 6.11).

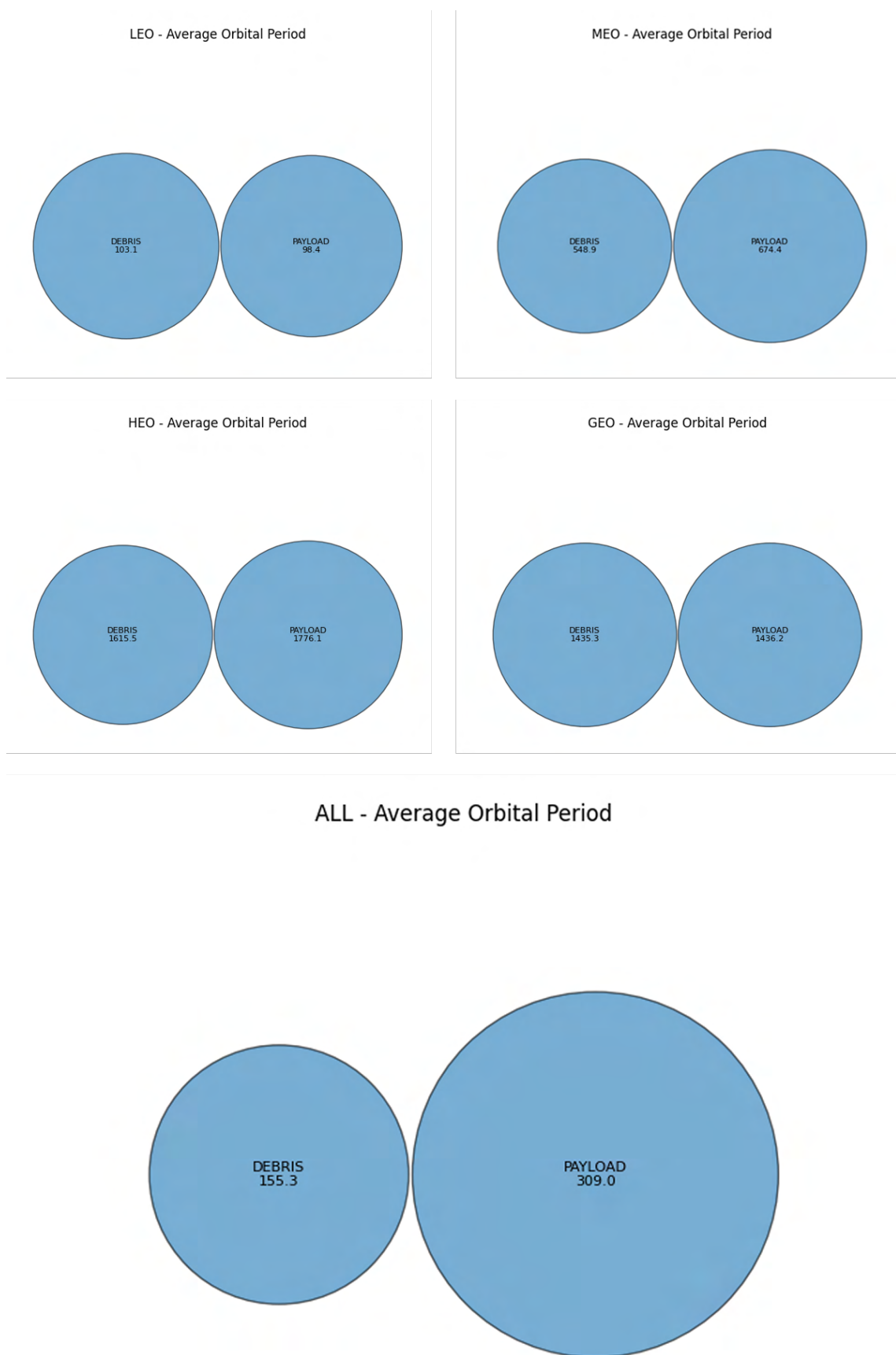


Figure 6.11: Bubble Chart of the Average Orbital Period for each Orbital Region

As can be seen, the graph with the most significant difference is when comparing all orbital regions, since the differences in other orbital regions are not as pronounced as when comparing all of them. Since the diameter of the gear determines the visualization on the vinyl, we decided to use the significant difference, rather than focusing on one orbital region specifically, so the multiplication of the gears could be better seen.

Having the ratio of the gears decided now it was time to design the mechanism, it was modeled after Maker's Muse video, so the design is not originally ours, since we could not find any file for the model itself like we did on the Orbital Debris Iris we needed to model the device from scratch having the video as a reference.

The design is pretty straightforward. Some rollers ensure the vinyl's movement is constant, and it utilizes skateboard bearings pressed into place with a diameter of around 8mm. Additionally, it features a stepper motor with an integrated gear reduction. The main structure uses 3D printing components to form the overall shape. However, it's also composed of an M10 threaded rod that incorporates some spatially positioned nuts to provide more clearance than usual.

Unfortunately, not having the exact model and having to model after a reference image and video caused some trouble. The model was created in Fusion 360 using the university license, but some of the measurements were not entirely correct, although they seemed fine at first glance when we finished the model (Figure 6.12).

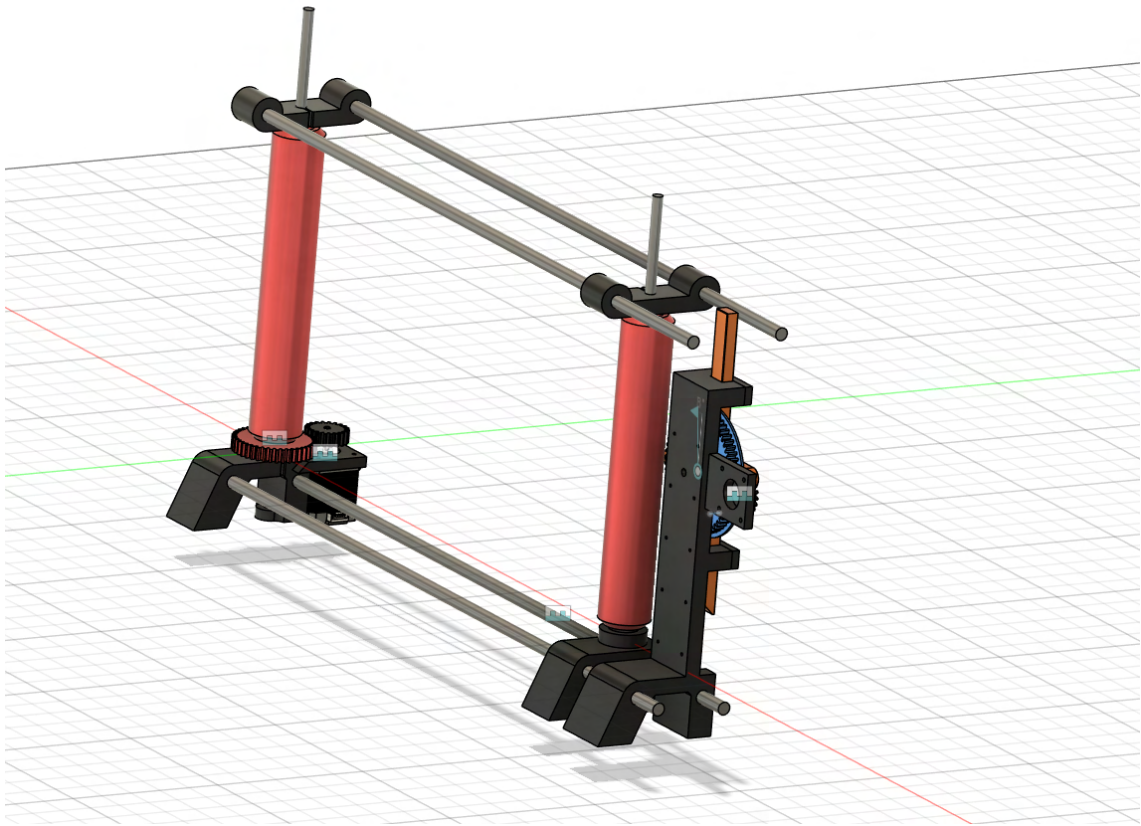


Figure 6.12: Fusion 360 model of Speed Track

One challenge was to compare both gears. To do this, it was necessary to have at least two Scotch yoke mechanisms positioned a significant distance apart (Figure 6.13). Creating this structure in real life would require a larger design, but it would be too thin and tall to reproduce effectively. Additionally, the limitations of a 3D printer with a printing volume of 26 cm x 26 cm x 26 cm mean that larger structures would need to be printed in separate pieces. This could create tension on the components during assembly. For these reasons, it was decided to print a modeled structure similar to the one in the video and to use two different gears to later illustrate the differences between them in photographs.

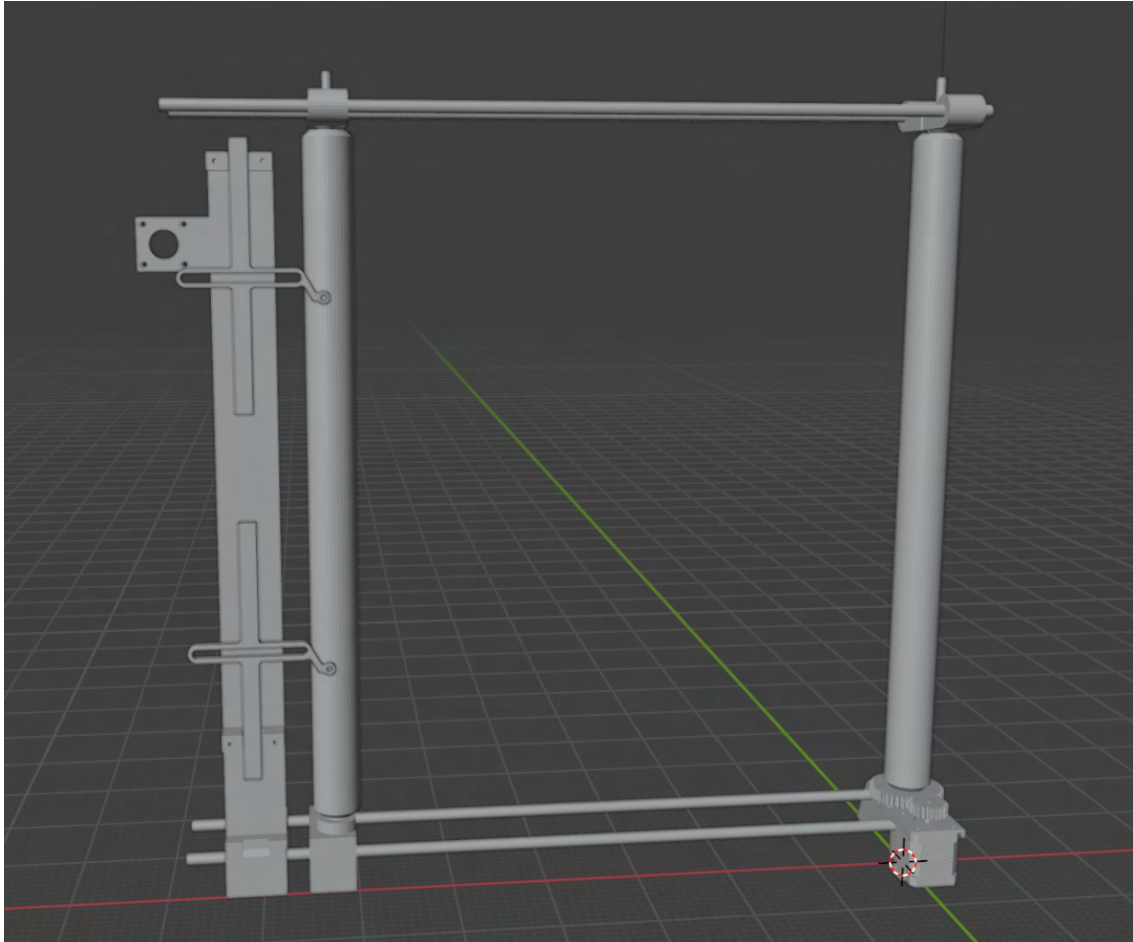


Figure 6.13: Speed Track expanded to comparison

The vinyl was also provided, and we used a simple UV LED and a 3V lithium battery to test the tracking (Figure 6.14). The fluorescent vinyl also glowed and left a track with other types of light, but the most effective one was UV light.

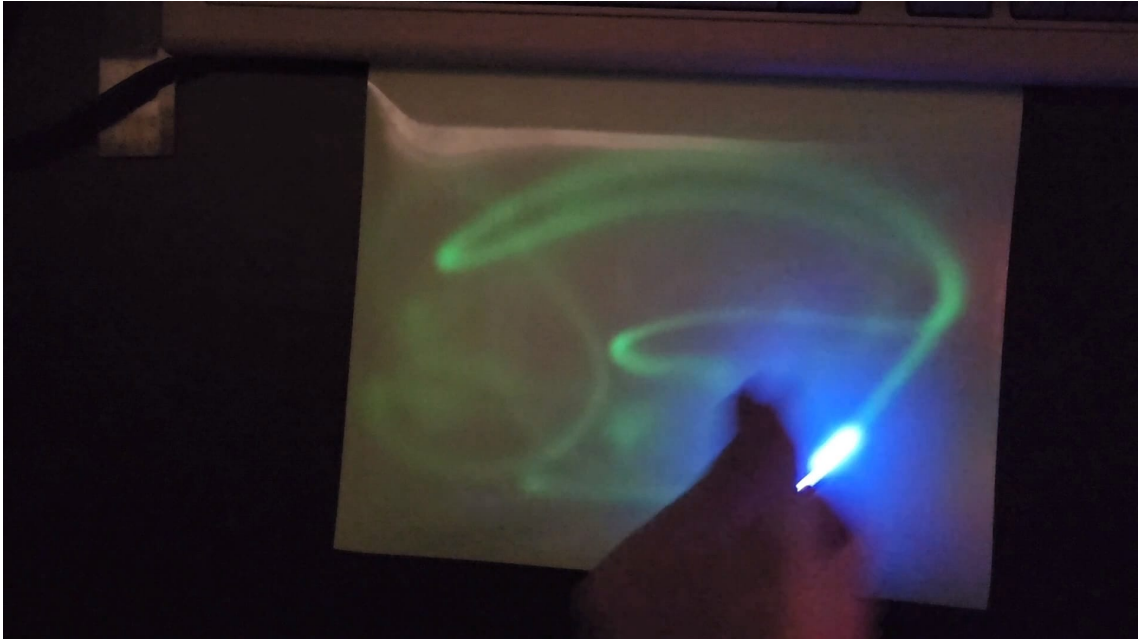


Figure 6.14: Fluorescent Vynil

The metal rods were also bought and trimmed to fit the structure (Figure 6.15)



Figure 6.15: Metal Rod trimming process

Unfortunately, when the parts were assembled several issues emerged. Some

dimensions extracted from the reference video did not correspond precisely to the printed components, compromising the alignment of the structure. Moreover, the M10 threaded rod arrived with a slight bend that went unnoticed until the frame was almost complete, this deformation jammed the rod inside one of the fittings. Additionally, one of the PLA parts fractured during the forced assembly, making the prototype structurally incomplete (Figure 6.16).



Figure 6.16: Incomplete printed Mechanism

Due to these setbacks and prevailing time and budget limitations, the mechanism had to be discarded, as had previous concepts. A three-dimensional render was then produced to illustrate how the mechanism would work (Figure 6.17).

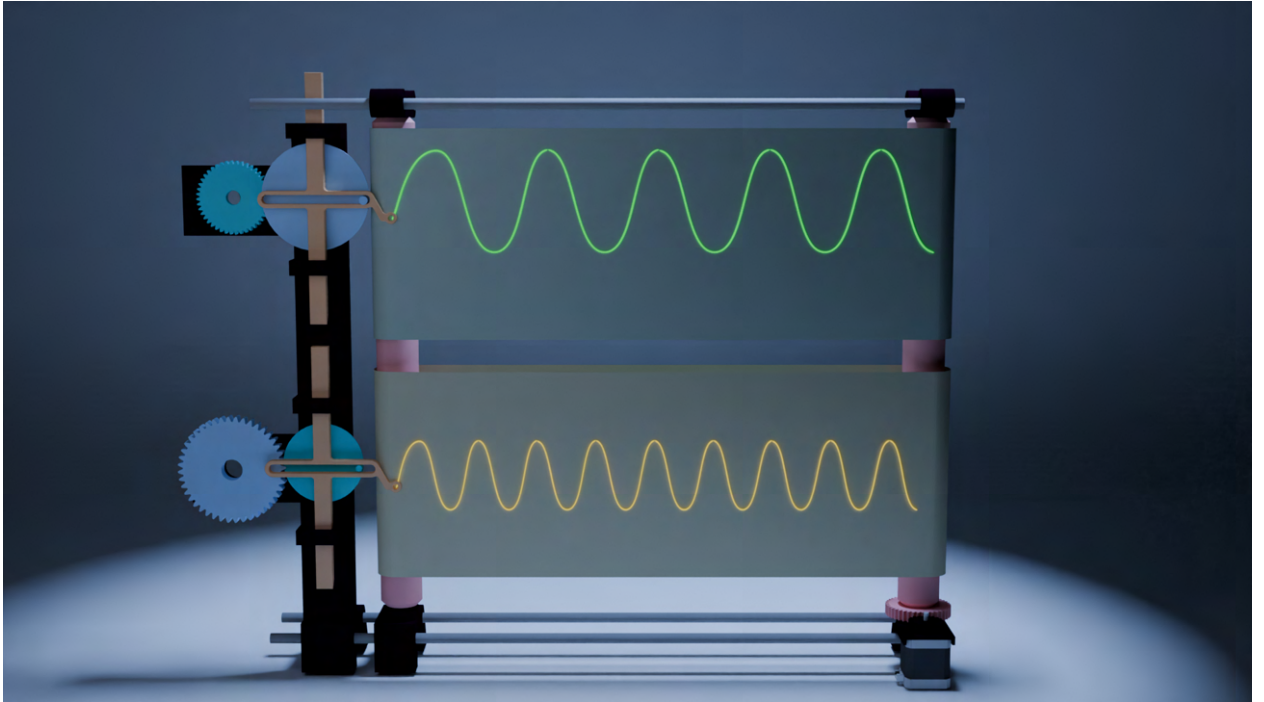


Figure 6.17: Gear Mechanism Render

For the render a simple spotlight and a few point light were used (Figure 6.18)

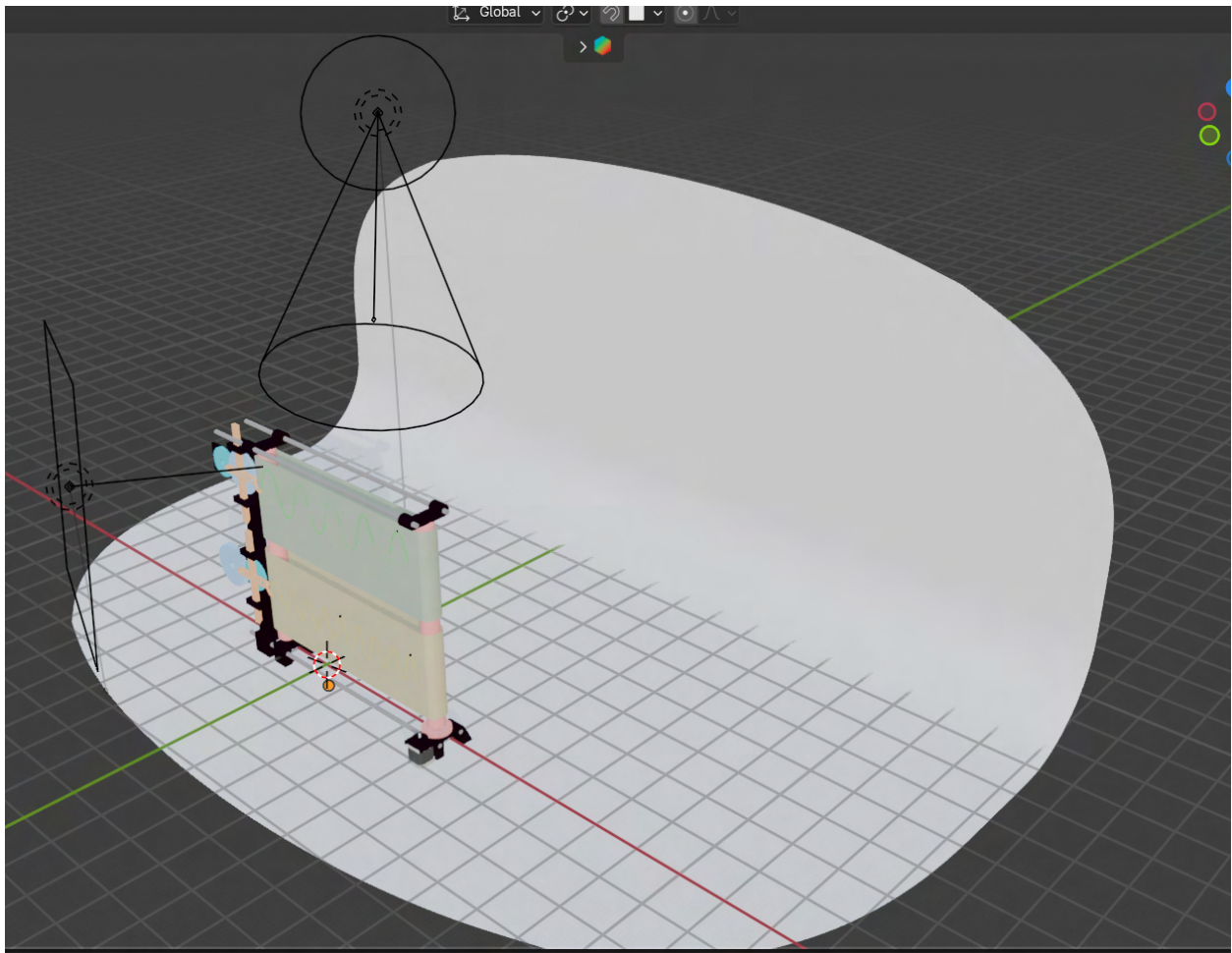


Figure 6.18: Render setup

6.4 Trash Mountain

While there were many attempts at creating an interactive physicalization that utilized electronics to automate data and display different aspects of it, another visualization that aligned more closely with the original experiments was the *Trash Mountain*. Inspired by the movie *WALL-E*, where humans abandon Earth and the planet becomes covered with piles of trash that grow into mountains, the metaphor seemed fitting: there is already too much debris in orbit, whether inactive payloads, rocket fragments, or shards generated by collisions. In the end, it is all the same: junk that we release into space. Some of it can be considered “useful junk” for a while, as it powers the systems we rely on, but sooner or later these objects also become useless or a collision risk. The more we launch, the greater the danger, and as a result, the mountain of orbital debris grows. The *Trash Mountain*, therefore, became a metaphor for what is happening in space right now.

6.4.1 Design intent and narrative

During this exploration, we came across Adrien Segal's "Snow Water Equivalent" [Segal], which documents thirty-one consecutive years of snowpack measurements at Ebbetts Pass in the Sierra Nevada (Figure 6.19).

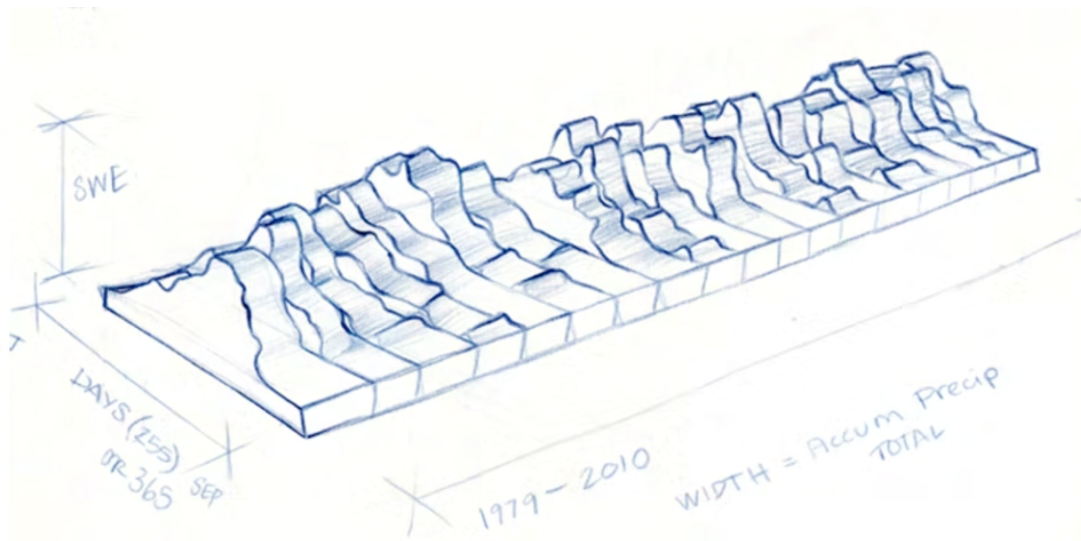


Figure 6.19: Snow Water Equivalent sketch [Segal]

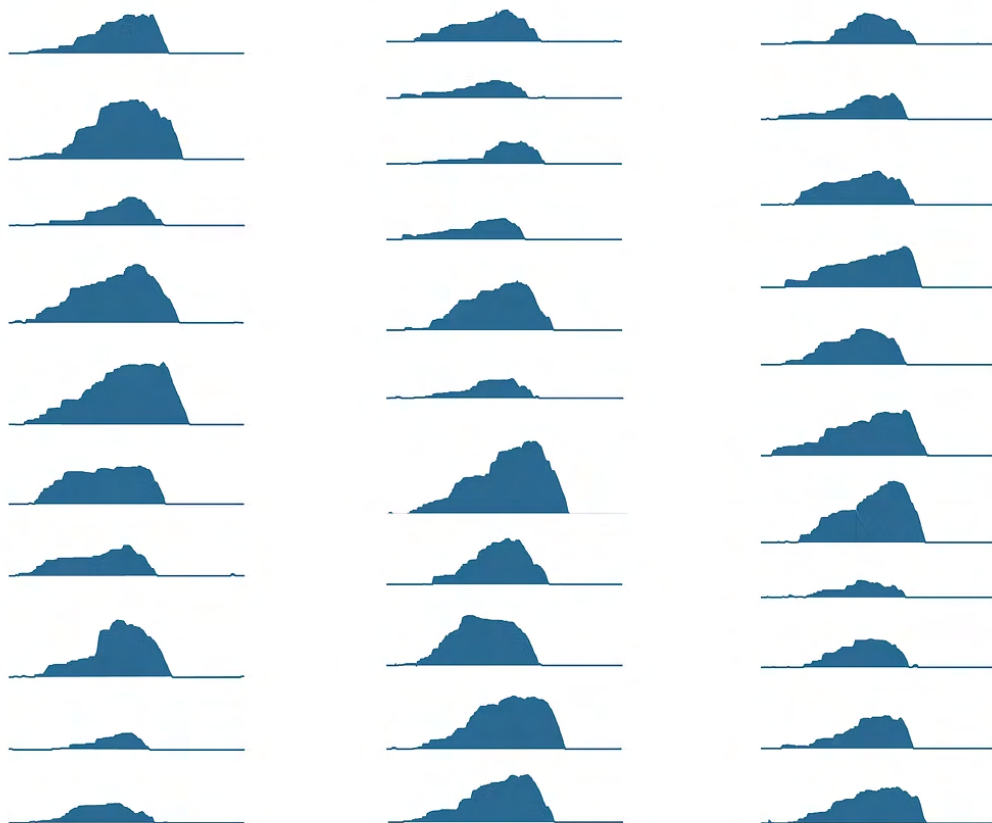


Figure 6.20: Snow Water Equivalent graphics along the year [Segal]

The author first charted the data (in spreadsheets) and then translated those temporal curves into a physical cabinet, where layers accumulate into a mass that visually and materially evokes a mountain. The days within each year and the years themselves are both present, producing a form that resembles the way snow piles up over time.

With that inspiration, the idea was to gather launches together with crashes and other relevant events over the years and show their cumulative buildup across decades, essentially creating a trash mountain similar to the movie. This approach shared similarities with earlier tests because, at its core, it was still a kind of transmediation: a three-dimensional bar chart of sorts. What set it apart was the clear intention and metaphor behind it. By this stage of the project, after several failed experiments, we had a clearer direction and a better understanding of how to shape the object into what we wanted it to be.

6.4.2 Visual encoding and layout

The first sketches were made in Blender, using its Python scripting to generate cubes for each data point. The goal was to represent the data along both years and months, in order to see whether clear patterns existed and if there were particular times of the Year with noticeably more launches. For that reason, the dataset was filtered to retain only the launch dates. The code imported the raw CSV and converted the launch-date values to valid date objects. From there, two new fields were created: the Year of the launch and the Month-Day in MM-DD format. This allowed us to group by Year and then by calendar day. For each Year, a bar chart of launches per day was plotted, highlighting seasonal fluctuations and days with heavy clustering of launches. Finally, the new dataset was exported to a new file, which was then used as input for the Blender script to generate the 3-D model of the mountain.

Initially the intention was to find relations on the data, between launches and months, we had no idea how the sculpture would look like so firstly we just gathered the launches and the months in a normal scale.

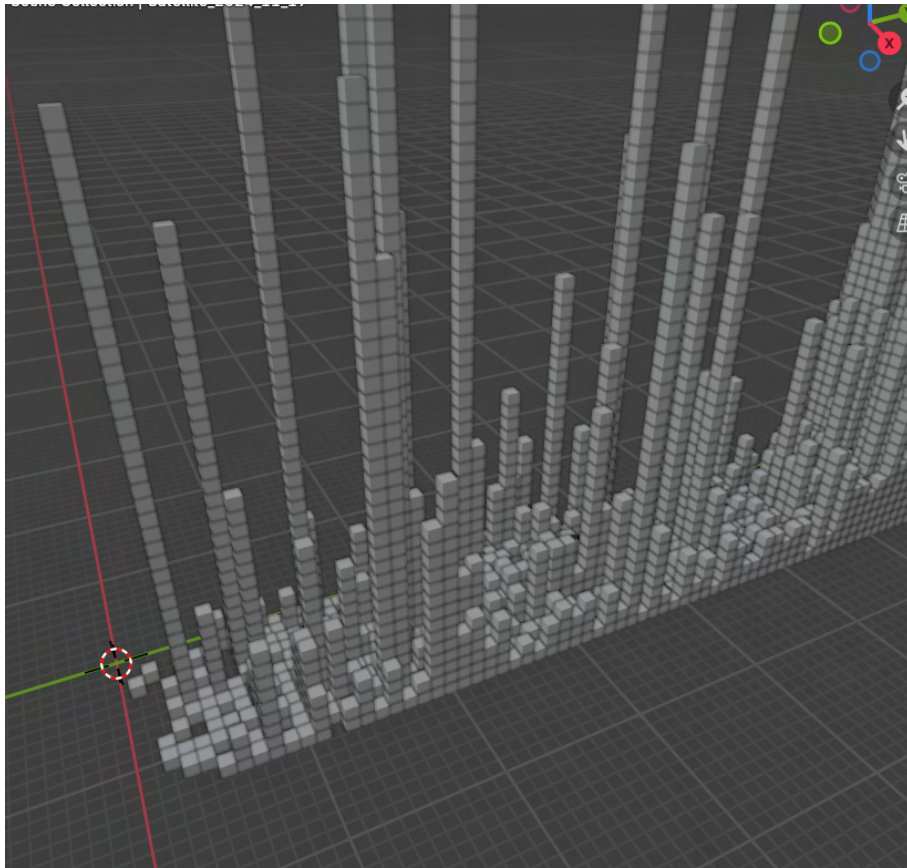


Figure 6.21: Trash Mountain first experience

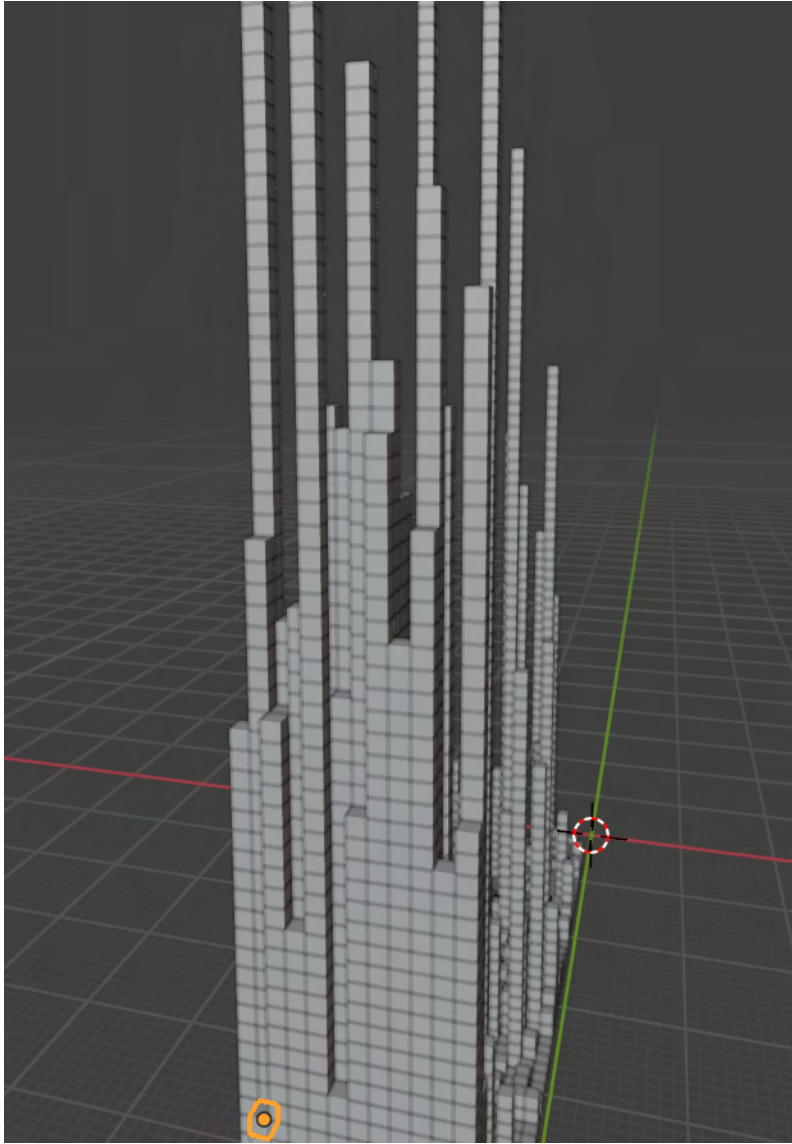


Figure 6.22: Trash Mountain second experience

At first, it was challenging to visualize patterns. Although the chart was divided by months, some towers were so tall that they occluded the rest, a common problem in 3D visualizations. There were too many objects packed into one month, so we could not see each day. Since they were packed into months over the years, this made it more challenging to read the data. Since the scale was making it difficult to see patterns, we decided to test again with all calendar days visible and with clear colors to differentiate between months.

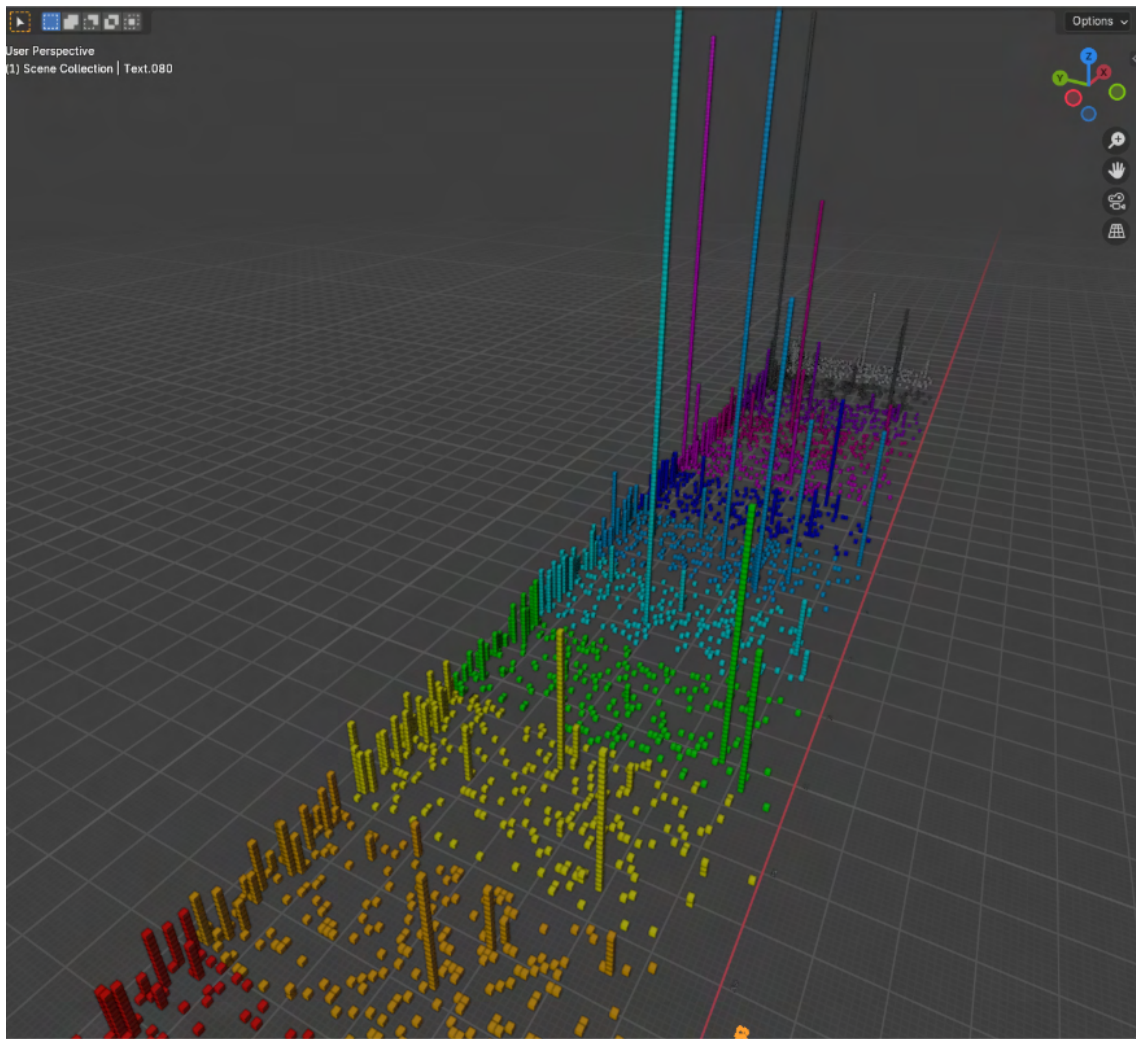


Figure 6.23: Trash Mountain without logarithmic scale, packed into Days along the Year

In this visualization, the month of May (cyan) stands out with more launches. For this first experience, we used a linear scale: one cube equals one event (launch or collision). With that assumption, the result appears better than before, with the peak in May being prominent, and the overall shape already resembling the intended trash mountain. However, to bring this idea to life, the total number of cubes and the maximum height matter. Keeping one-to-one cubes would push the tallest tower to more than 50 meters, which is entirely unviable for fabrication and exhibition.

We tested a logarithmic scale to reduce the height. It solved the fabrication issue but created new problems: it was less aesthetically pleasing than the linear stack, and it flattened the very peaks we wanted to emphasize on the visualization, the “mountains” almost disappeared. Our solution was to aggregate events into cubes. Each cube stands for a fixed number of launches (and collisions). This keeps the linear look and preserves the differences between months while keeping the sculpture within practical limits. The result remains dramatic, it’s still possible to read all the data and understand the amount without requiring an overly complex structure.

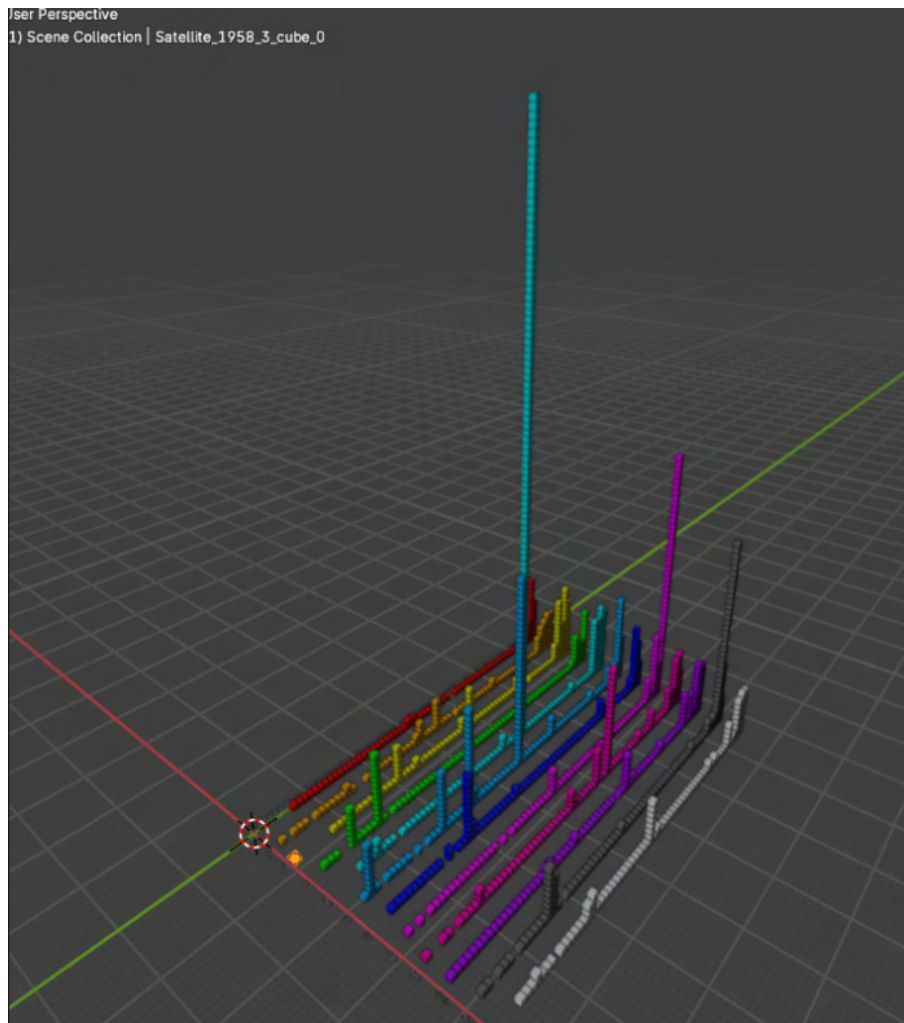


Figure 6.24: Trash Mountain without logarithmic scale, packed into Months

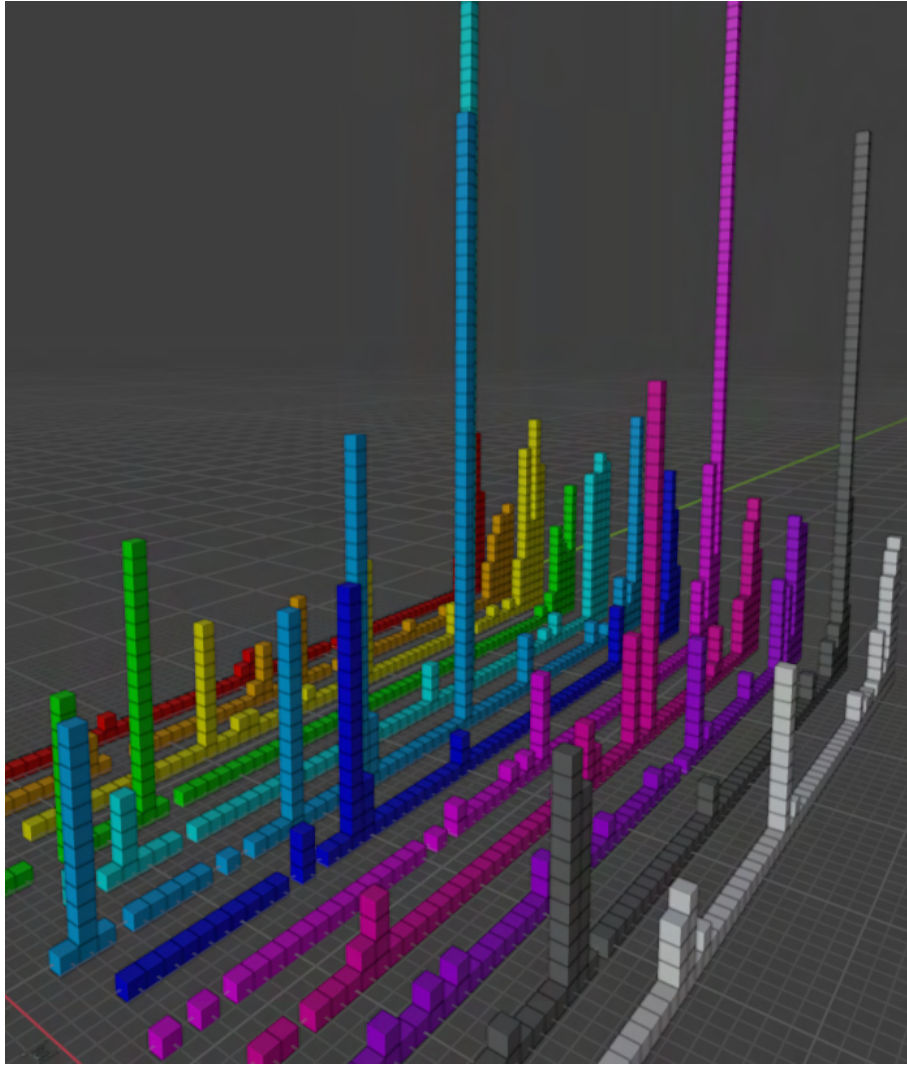


Figure 6.25: Trash Mountain without logarithmic scale, packed into Months

One of the first results (Figure 6.25) listed all the years and set each satellite to be equivalent to five cubes. This version already makes the peaks clear and shows when launch activity begins to climb. To achieve a closer approximation to the intended sculpture, we fixed the cube size at $2\text{ cm} \times 2\text{ cm}$. The goal was visibility and impact: big enough to read and feel from a distance, but not so big that the build became unmanageable. Because the problem we are discussing is significant in scale, a larger object helps reinforce that message.

6.4.3 Fabrication and constraints

The piece needed a base. Considering the cumulative weight, we chose a wooden base that serves only as structural support. It was painted black to give the sculpture more contrast. Before painting, we sanded the surface to get a smoother finish (Figure 6.28).



Figure 6.26: Base painting process

For the cubes, we first tried wood (Figure 6.27). Making even a single cube required too much manual work, as we were cutting a bar by hand with a saw. Repeating that hundreds of times was not realistic.



Figure 6.27: Wood Cubes

We switched to 3D printing. Printing would take longer per cube, but it required far less physical effort and gave consistent 2×2 cm cubes. At first, we planned to print more than a thousand cubes. That quickly proved unviable: the sculpture would become too large, very difficult to transport, and structurally risky, a problem that we had initially wanted to avoid. With a footprint of only 2×2 cm, the tallest stacks could exceed two meters and would be prone to tipping. We returned to the Blender model and modified how cubes were aggregated. After testing several values, we determined that 69 launches per cube was optimal. This maintained the overall form's visual strength while keeping the build manageable, with a total of 480 cubes.

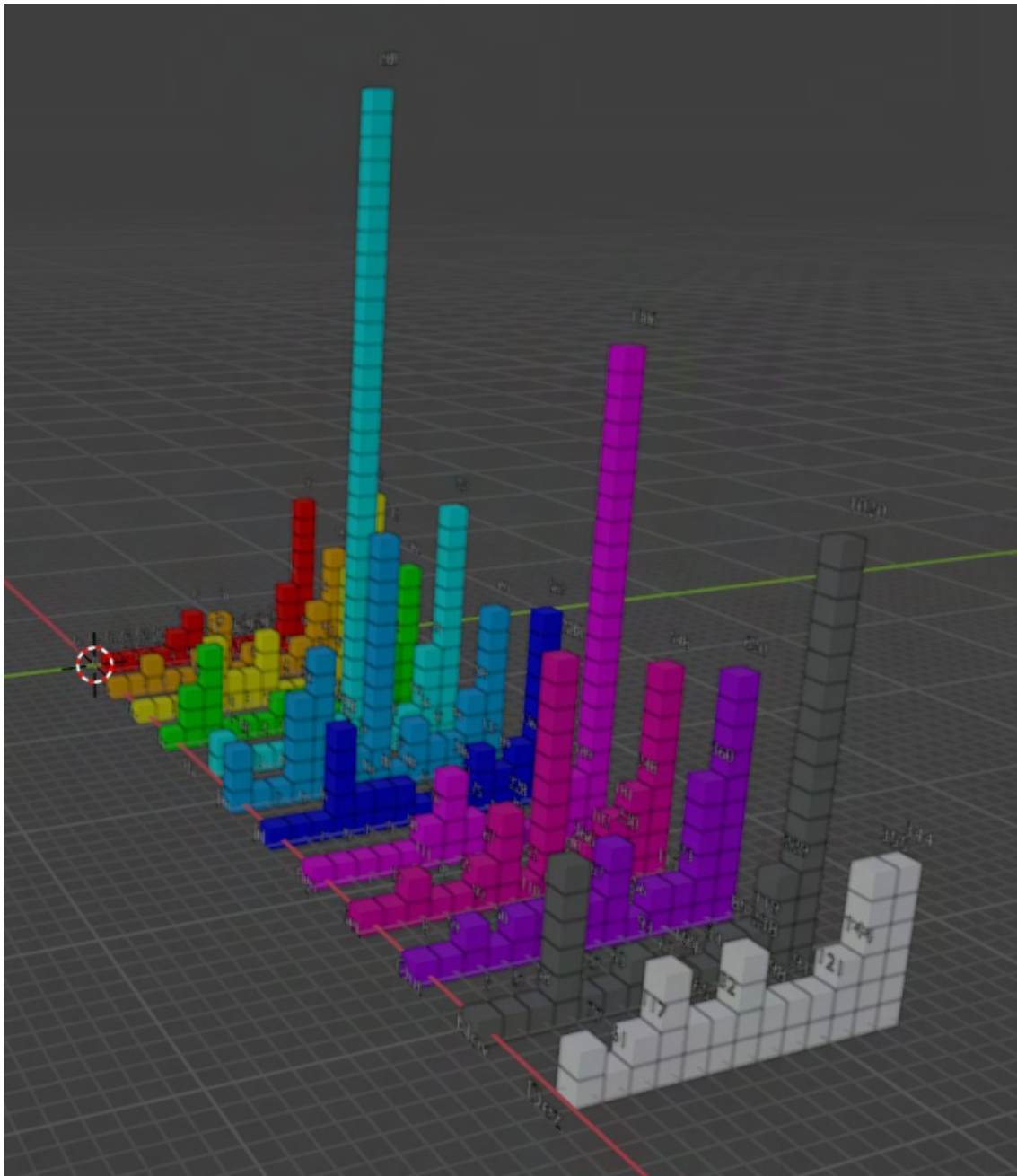


Figure 6.28: Trash Mountain without logarithmic scale

For the painting process we were inspired by the movie *Wall-e*, so we wanted to have the effect they have in the movie, with the trash mountains having many colors. We used the movie pictures as a reference of how we could make the painting of the cubes, with a few modifications (Figure 6.29).



Figure 6.29: Wall-e Movie inspiration

The script was updated to group the years into 5-year intervals, to maintain a practical limit on the total number of cubes. It reads the CSV, filters by object type, bins every record into a five-year row and a month column, determines how many cubes each cell receives, and then builds the stacks with one color per month. It also writes simple labels for axes, stack totals, and the current scale for visualization process.

With this, we keep the linear scale, preserve the month colour coding, and keep the large peaks visible. Each Blender unit cube also corresponds to the physical cube size we set for the sculpture. The current grid uses a fixed spacing of 4 units in X. This keeps stacks separate and makes room for the labels.

Before painting, we first glued the cubes together. Initially, we used superglue, but it proved too troublesome to rely on it alone: we always had to sand the faces that would be joined, and any gap made the bond fragile because superglue requires complete surface contact. After using this method for two towers, we switched to hot glue. Hot glue didn't require all those extra sanding steps, it was a matter of simply applying and pressing the cubes together, allowing us to build it faster.

The main disadvantage is that hot glue can be weaker than superglue, and if the joint isn't held in place while it cools down, it can get slightly crooked. For small towers, this wasn't a problem, having a bit of distortion even looked good (Figure 6.30). For the large tower, it was different: the stack was really tall and sometimes too bent to stay perfectly upright. The big tower collapsed a few times due to its size, requiring it to be rebuilt several times.



Figure 6.30: Glued Towers

Painting was the most time-consuming part. We started with primer and covered the entire tower so the surface looked smoother and the layer lines would be less visible (Figure 6.31). Primer also helps the paint adhere to the surface instead of being partly absorbed by the 3D-printed texture. The primers used were white and black primers simply because they were the ones we had available.



Figure 6.31: Priming process

For the painting part we divided in some steps, first we applied a base color, that in our case was beige (Figure 6.32)



Figure 6.32: Beige base color

Then we added multiple colours inspired by the film: yellow, pink, green, blue, orange, copper, brown, and yellow ochre (Figure 6.33).



Figure 6.33: Painting process

Then we added multiple colours inspired by the film: yellow, pink, green, blue, orange, copper, brown, and yellow ochre (Figure 6.33).

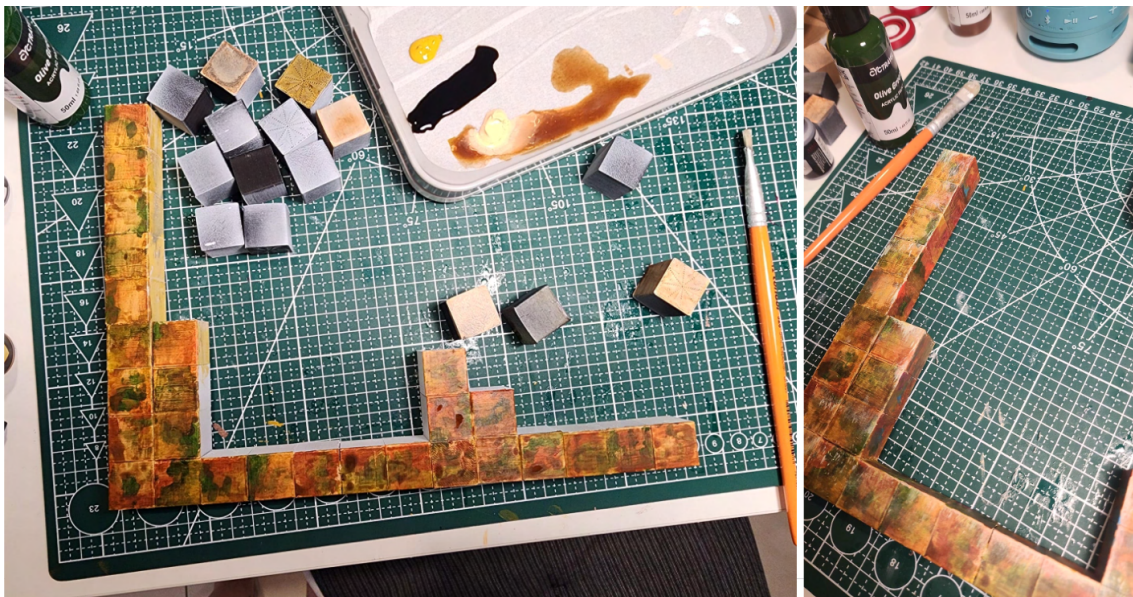


Figure 6.34: Wash applied

Next, we applied washes, which are significantly diluted paint in water, to unify everything and achieve a dirtier, “trash mountain” look. We used brown, flesh wash, and grey. There wasn’t a strict rule here; these were the washes we had, and they did the job.



Figure 6.35: Base color application

For the final touches, we used dry-brushing with white paint to pick out edges and highlight each cube. This helps people read them as separate units while still understanding they belong to the same group (the months) (Figure 6.36).



Figure 6.36: Dry brushing technique

Finally we assembled the sculpture, above the wood base (Figure 6.37).

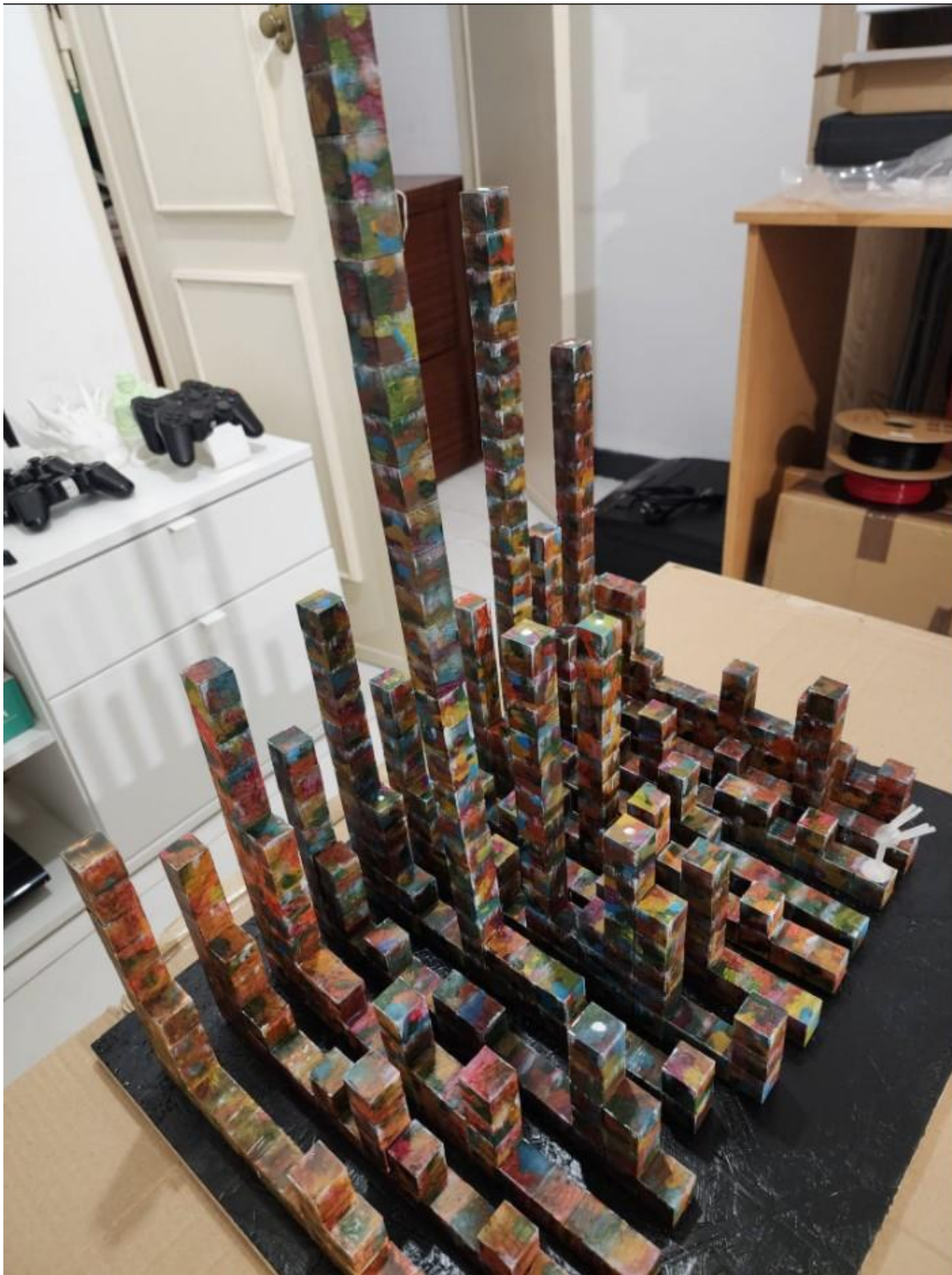


Figure 6.37: Trash Mountain assembled in wood base

The sculpture looked good, but we wanted to enhance its ability to convey the main historical events that contributed to orbital debris. With that in mind, we decided to model a few collision and fragmentation milestones and place them as marks on the piece. The table 6.2 below lists the selected events, what happened, and an approximate fragment count when available.

Table 6.2: Selected events related to orbital debris and accumulation of objects.

Date	Object	Event	$\approx$ Fragments	Source
Oct, 1957	Sputnik 1	First artificial satellite launch	—	[History]
Apr, 1970	SL-8 / Kosmos 367 R/B	Upper-stage explosion in LEO	~ 280	[Anz-Meador et al., 2023]
Jun, 1981	Kosmos 1275	Breakup attributed to internal failure	~ 300	[ODQ, 2022]
Jan, 2007	Fengyun-1C	Chinese ASAT test destroyed FY-1C weather satellite	~ 3.000	[Johnson et al., 2007]
Feb, 2009	Iridium-33 $\times$ Cosmos-2251	First accidental collision between two intact satellites	> 1.800	[Shepperd, 2023]
Nov, 2015	NOAA-16	Spontaneous breakup of weather satellite	~ 200	[odq, 2016]
May, 2019	Starlink (constellation)	Frequent launches of ~ 50 – 60 satellites per mission; marks megaconstellation and number of space objects growth	n/a	[Thompson, 2019]
Nov, 2022	Long March 6A (Y2) upper stage	In-orbit fragmentation of CZ-6A upper stage	> 700	[Jones, 2024]
Aug, 2024	Long March 6A (Y4) upper stage	Another CZ-6A upper-stage breakup after launch	~ 600 – 700	[Wall, 2024]

6.4.4 Modeled objects

For these marks, we first considered modelling every event individually, but that would be too time-consuming. Since several events were similar to each other, such as satellites and rocket bodies fragmenting on their own or collisions between objects, we decided to categorize them accordingly. The categories used were:

- **Sputnik 1.** A dedicated model only for the first satellite launched.
- **Fragmentation along the years.** Cases where satellites or rocket bodies fragmented without interference from other objects, they turned into debris by themselves.
- **Rocket and satellite collision.** A specific mark for the single case where a satellite was destroyed by a directed rocket, not by degradation or by

any other satellite, we made an exclusive structure for this, since it also corresponds to the tallest tower in the sculpture.

- **Satellite collisions.** Events involving more than one body colliding with each other.
- **Starlink.** A mark for the recent increase of objects in orbit, with Starlink, we started having many more launches per year.

We designed a simple base for all marks and printed it in transparent filament so the objects would appear to float over the sculpture. The base is a circular foot with a vertical cylinder that holds each mark (Figure 6.38).

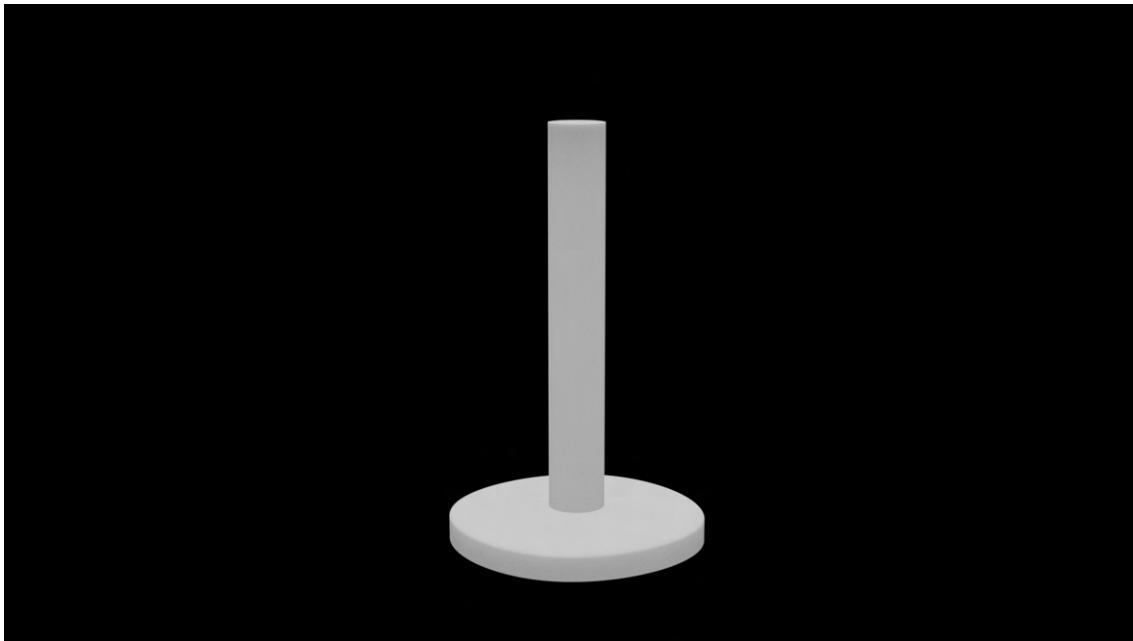


Figure 6.38: Base modeled for the marks

Although the filament was chosen to be transparent, printing with walls and infill produces a milky, almost white appearance rather than a clear one. This worked in our favour: we wanted the marks to read as distinct from the sculpture. We considered painting them, but their unpainted look made all marks more uniform and easy to identify. Painting would reduce that contrast and could blend them into the main piece that already has too many colors. The goal was to keep them as distinct objects, but still part of the same whole, using a different encoding.

For the **Sputnik** mark, we modelled Sputnik itself. Due to printer tolerances, the struts could not be as thin as the real object, so we used thicker elements (Figure 6.39).

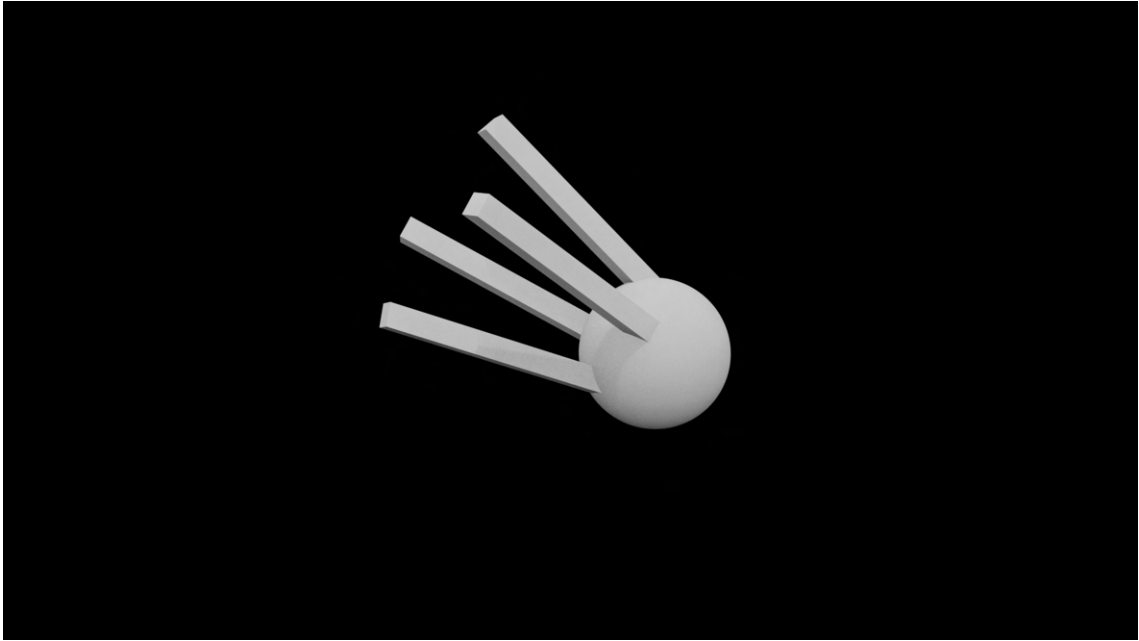


Figure 6.39: Modeled Sputnik 1

For the **Fragmentation**, we created an object resembling a sphere of shards, to suggest a body breaking apart from within over time (Figure 6.40).

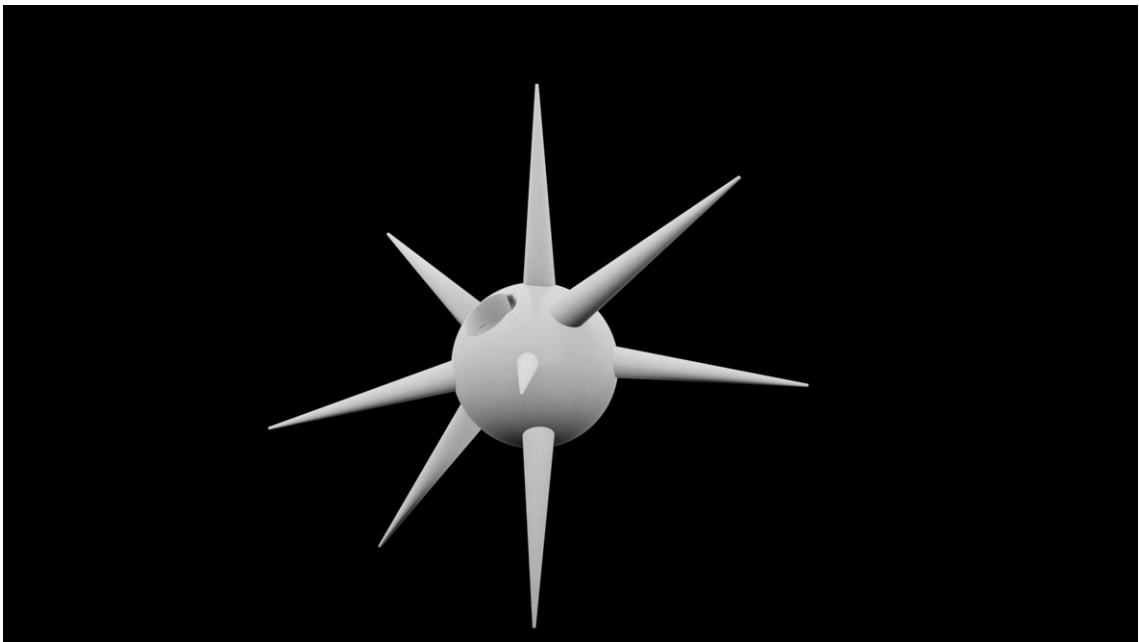


Figure 6.40: Modeled Sphere of Shards

For **Satellite Collisions**, we modelled two simplified satellites close to each other, as if they were about to collide: a central rounded rectangle for the main body and smaller rounded rectangles for the solar panels. There was no reason to overcomplicate this step, the intent is for the icons to resemble an icon more closely than a detailed scale model (Figure 6.41).



Figure 6.41: Modeled Satellites Colliding

For the **Rocket destroying a Satellite** mark, we reused a rocket model from a previous work and placed it where the second satellite would typically be. This represents the only case of a satellite destroyed by a directed rocket and also marks the tallest tower (Figure 6.42).

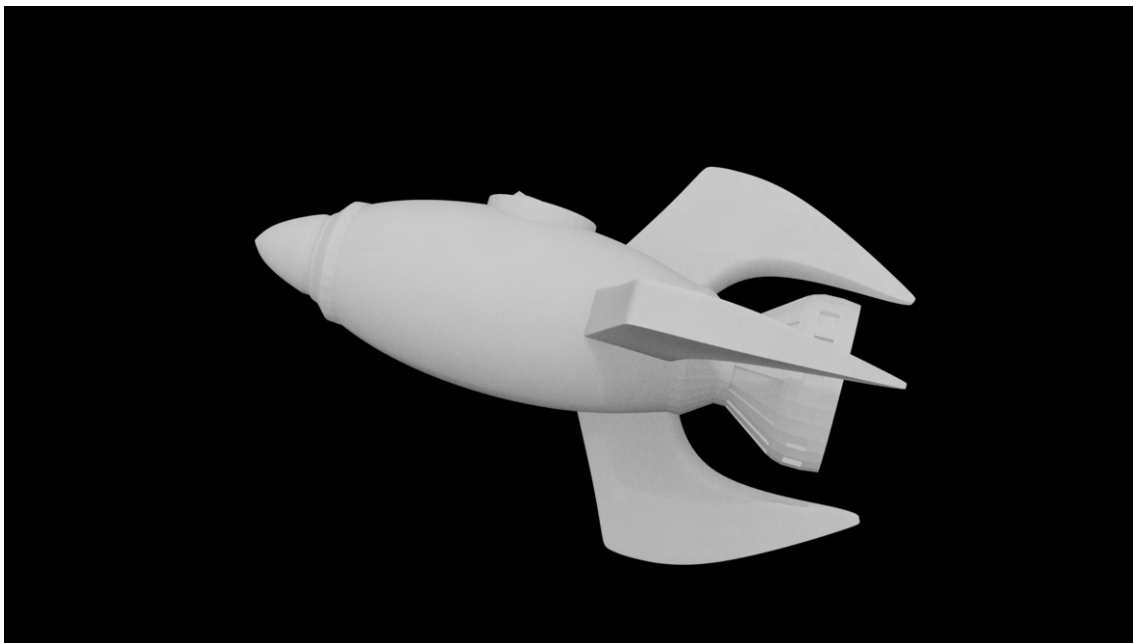


Figure 6.42: Modeled Rocket

For **Starlink**, we were inspired by how Starlink looks from Earth. Instead of modelling individual satellites, we represented them as many small boxes in a line (Figure 6.43), echoing how we see Starlink: a sequence of small light points moving one behind another in the night sky.

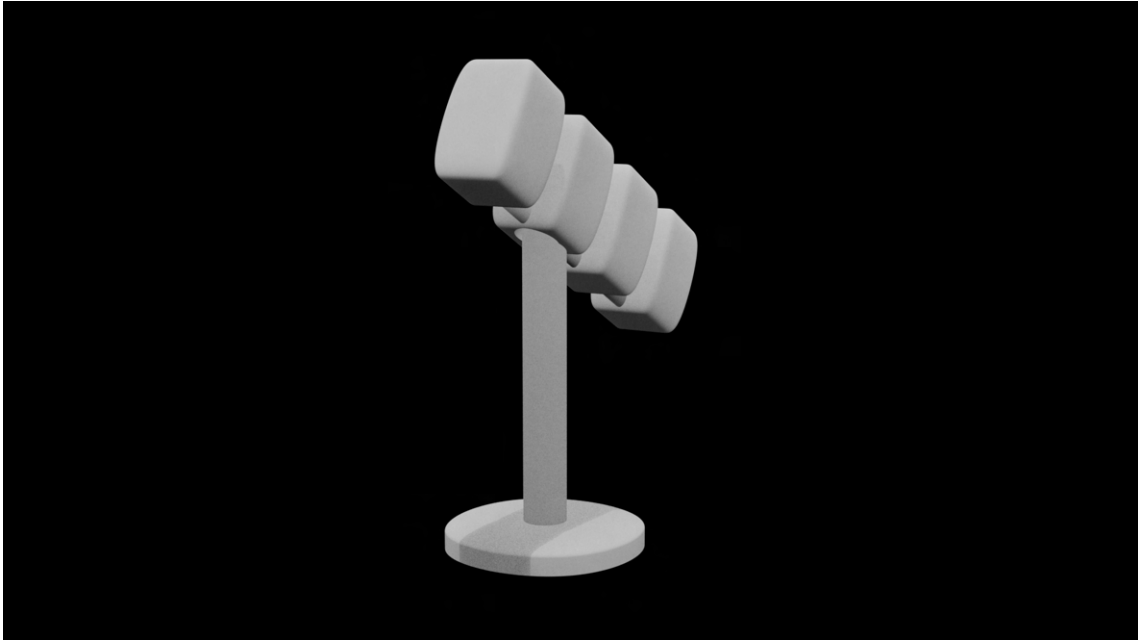


Figure 6.43: Modeled Starlink

6.5 Discussion

This chapter refined the project's direction from an open exploration to more scoped artifacts that better aligned with the awareness goal. The motion tests with the zoetrope demonstrated that movement may not guarantee legible data, at least not with the type of data used in this experiment. The idea was discarded, but it clarified an important constraint for this project: if motion does not add precision or insight, it is noise.

The *Orbital Debris Iris* validated the mapping conceptually (growth over time encoded as diameter) but exposed practical limits in fabrication and actuation. Tolerances, friction, and torque requirements exceeded what was possible within the current resources.

The *Speed Track* pushed a different narrative (relative orbital periods/speeds) and clarified two issues:

1. Translating kinematics into traces is explainable and visually distinctive;
2. The mechanical development and alignment made the device sensitive to small modelling errors. The mechanism did not reach a working state.

The *Trash Mountain* advances the campaign most effectively. The accumulation metaphor is immediate, the month encoding remains visible, and aggregation by fixed cube counts keeps the piece fabricable, transportable, and legible at exhibition scale. Although there may not be indications of the scale on the piece itself, it will be added digitally to the campaign material, allowing the piece to remain more as a piece of art, specifically data art in this case.

Two overarching conclusions follow. First, the iterative approach was necessary: earlier experiences prevented some later rework, and the working constraints (time, budget, tooling) were as decisive as the data mappings themselves. Second, some planned work could not be concluded, such as motorization, full mechanism builds, and especially user testing, as we did not have time to test the final object. These limits should be accounted for when planning projects of this scope, as mechanical tolerances and actuation choices have a greater impact than anticipated. Many of the main issues were mechanical and more related to engineering, which is not our area of expertise. Therefore, some of these problems may not be as significant for someone who has already addressed various engineering challenges. We ultimately adopted a more artistic approach for the final sculptural piece, which conveys the core message of the campaign and establishes a practical baseline for the next chapter's materials.

Chapter 7

Awareness Campaign

This chapter presents the awareness campaign built around the physical sculpture developed in the previous chapter. The goal is to translate the project's core messages on orbital debris into materials that are clear and legible.

7.1 Target Audience

Defining the target audience is crucial for any awareness campaign because it dictates what information is shown, how much detail is appropriate, and which visual language will be most effective. For this project, the target audience was high-school students (approximately 14–18 years old) who visit the Department of Informatics Engineering (DEI). These visits occur regularly throughout the academic year, making this group both reachable and relevant. By focusing on that demographic, we can calibrate the narrative and data density so the visualisations remain engaging without overwhelming first-time viewers.

7.2 The Concept

The campaign centres on the Trash Mountain sculpture as a clear metaphor: make orbital debris feel like a growing pile of waste. The reference is quite explicit from the movie *WALL-E*, which depicts cities covered by stacked trash that form mountains. We borrow that image to discuss space: objects do not disappear, they accumulate and form a mass with weight and shape.

The mapping follows this idea. Horizontal layers of five-year bands represent years, and vertical stacks represent months. From a distance, the piece appears as a single mountain silhouette: the problem has a distinct body and contour. Up close, the viewer can better see the structure, so the metaphor does not obscure the data. Key events are placed above the surface to provide context for what happened in some years, highlighting the history of space debris.

The material language supports the concept as well, using cubes with 2 x 2 cm to

give the work a physical “weight” without losing legibility. The painting work takes direct inspiration from *WALL-E*’s trash palette (warm, varied, worn), but stays secondary to the grid so the data remains readable. A black wooden base frames the object, keeping attention focused on the mountain itself.

7.3 Pictures

We photographed the piece at the department using an improvised setup. A white sheet served as the background and was taped in place to hold it (Figure 7.1). With this setup, we captured the images used in the campaign and the infographics, allowing us to add annotations and tell the story we wanted to convey. We also used a small turntable to help rotate the structure while shooting. For the infographics, we selected images taken from a slightly isometric angle so the information would be more visible, additional photos from other angles were also taken.



Figure 7.1: Photoshoot setup

The pictures were later processed using Photoshop to remove the background and adjust color balance (Figures 7.2). More pictures can be found on the Appendices



Figure 7.2: Sculpture pictures

7.4 Visual Materials

This chapter presents the awareness campaign built around the physical sculpture developed in the previous chapter. The goal is to translate the project's core messages on orbital debris into materials that are clear and legible.

7.5 Process

After selecting and processing the photographs in Photoshop, we started the graphic work. We chose the most isometric image as the base for the first infographic and removed the background to isolate the sculpture (Figure 7.3).

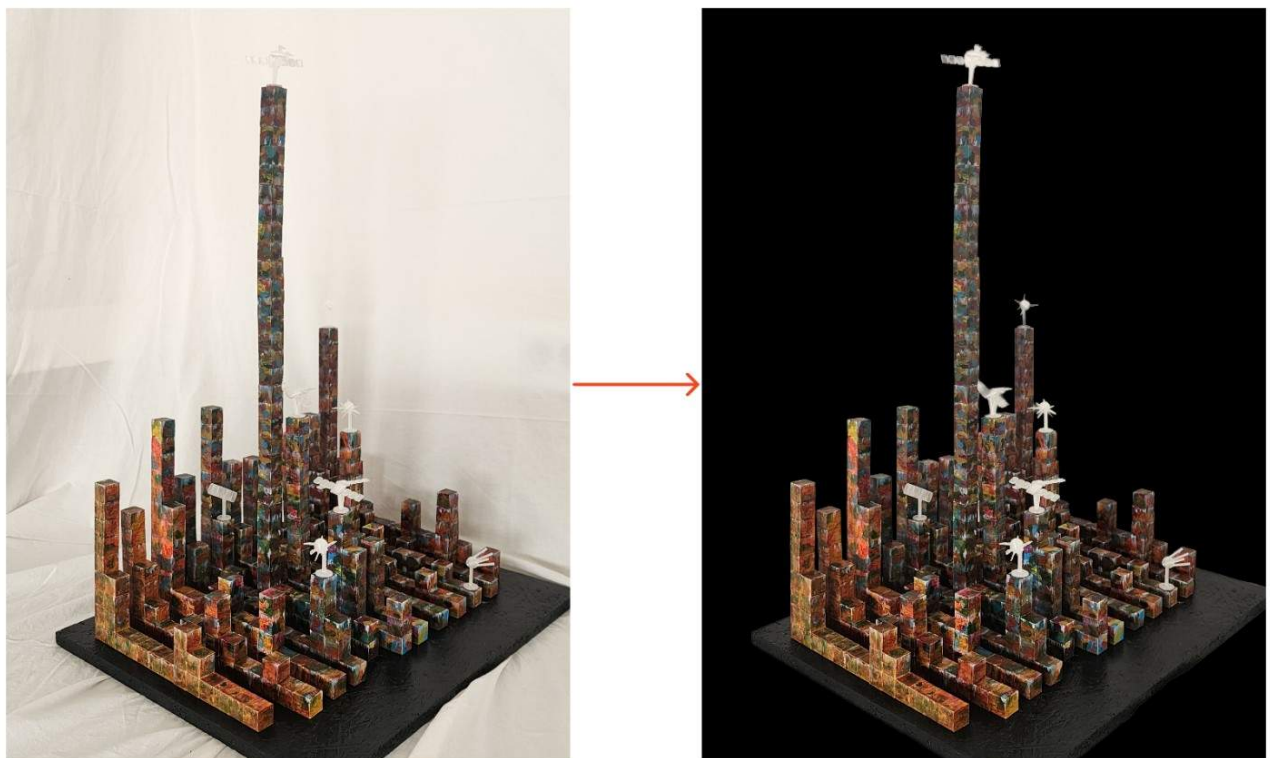


Figure 7.3: Removed the background of the main isometric picture

We tested several layout options with this image (Figure 7.4), exploring placements for labels and axes. These trials helped to better see where annotations could be placed without obscuring the relevant parts of the piece.

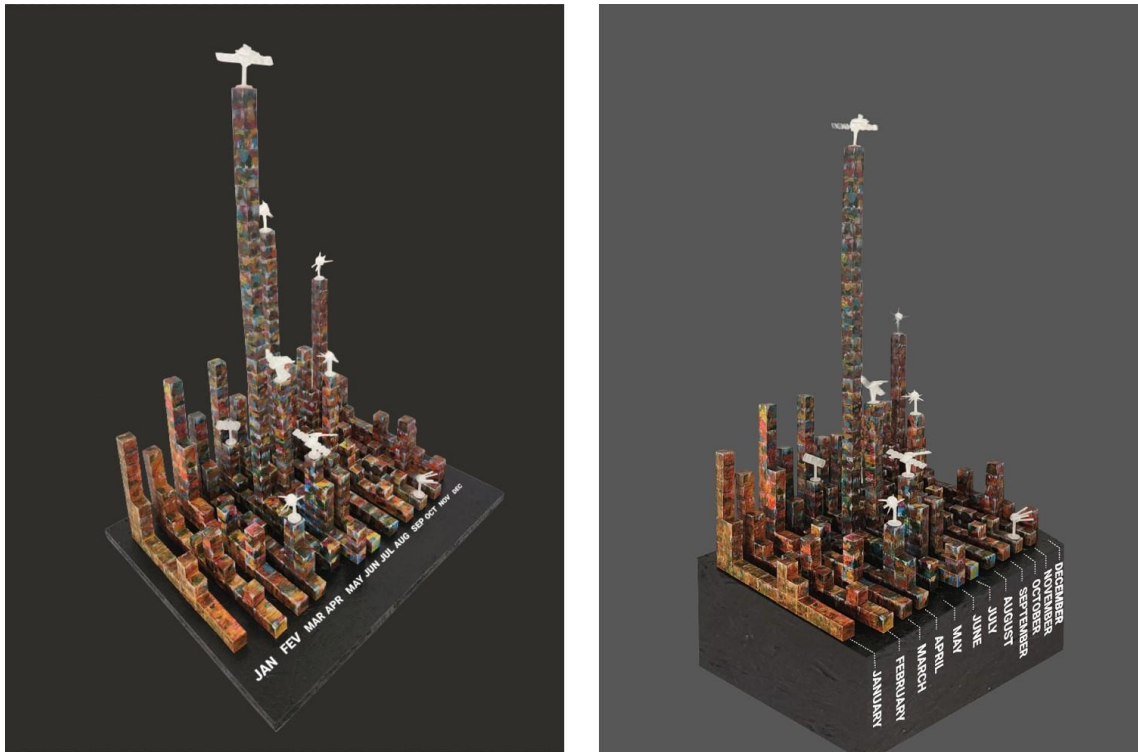


Figure 7.4: First layout annotation experiences

We discarded the initial layout because it was not sufficiently readable and switched to an isometric grid. The grid allowed us to align the photograph and define a clear guide for the annotations. With the grid in place, we created a base layer to position the labels consistently and keep the dashed lines aligned to the grid, some marks of the sculpture picture were also changed so it would be more readable (Figure 7.5).

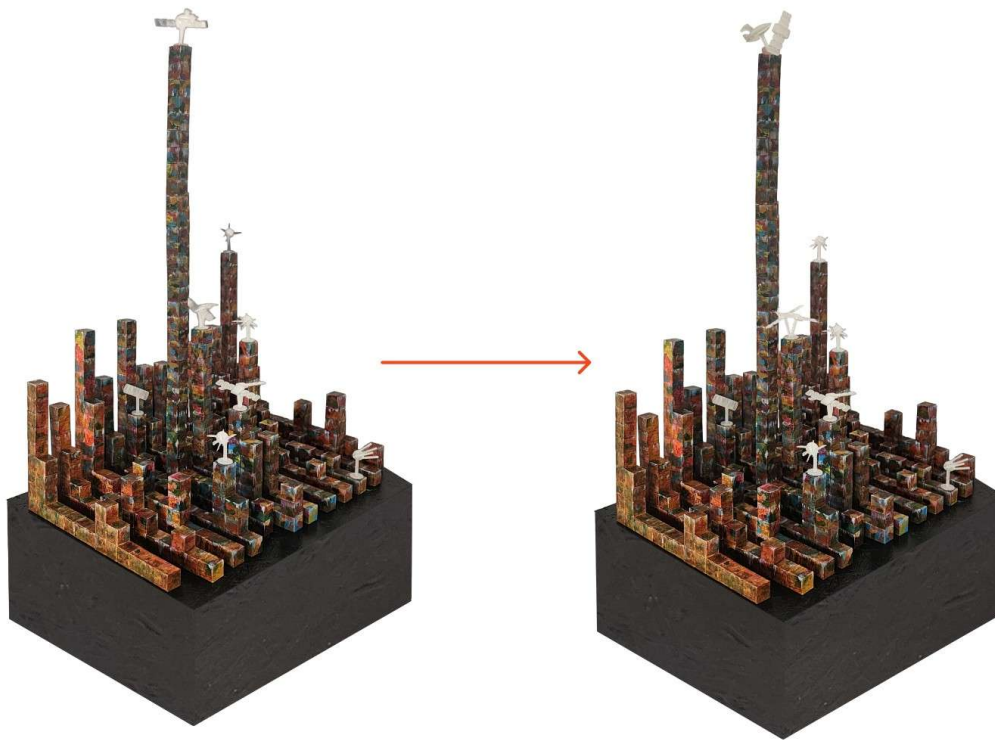


Figure 7.5: Picture adjusted along the isometric grid and with a base

Further layout experiments are documented in the appendices. The final isometric graphic features a subtle gradient background to enhance contrast and depth, with annotations on the image about the events that happened over the years. We also added additional information on the number of launches per year and month, so the piece reads at a glance while still providing context when viewed up close and it's possible to read the small text.

7.6 Infographics

In the process, we tested several background gradients, and the ones that provided more contrast were the darker ones. We also used black at the bottom with a dark color on top to make the piece more interesting, it was bland without these additions. The palette deliberately borrows from colors commonly seen in astronomical imagery, such as nebulae, so dark green, dark purple, and blue were the most interesting options for this context. We did not want the base to appear, so the black lower field visually makes the base disappear and lets the ticks for the data be more visible (Figure 7.6). This creates a better separation between the sculpture and the annotations without introducing additional frames or boxes that would visually compete with the object.

TRASH MOUNTAIN

Space is filling up, and we depend on it more than ever. Satellites make modern life possible with GPS, internet, weather and communication.

When a rocket explodes or a satellite dies, their parts keep orbiting around Earth at several kilometres per second. One collision can shatter into thousands of pieces that can hit other objects and create even more debris. If we keep launching without cleaning up we will create more piles of debris orbiting Earth making space missions risky and the systems we rely on be interrupted or lost.

Each cube represents

69 satellites



Iridium 33 × Cosmos 2251

First collision between two intact satellites
>2300 debris

Fengyun-1C

Chinese anti-satellite missile test
>3000 debris

Long March 6A

Second stage of a rocket fragmented weeks after launch
>700 debris

NOAA-16

Defunct weather satellite breaks apart on its own
>400 debris

Starlink

First batch of 60 satellites, start of mega-constellations

Cosmos 1275

Operational Soviet satellite hit by untracked fragment
>300 debris

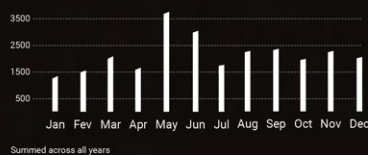
Nimbus 4 Upper Stage

Rocket stage explodes in orbit
>400 debris

Sputnik 1

First artificial satellite launched

OBJECTS PER MONTH



OBJECTS ALONG THE YEARS



Figure 7.6: Final isometric infographic with dark gradient

Regarding the annotations, we wanted the title to be the first thing someone looked at when they saw the infographic piece, so its position reflects that priority: the reader reads first *Trash Mountain* and then their eye is drawn to the sculpture (Figure 7.7).

To reinforce that reading path, we maintained a clear typographic hierarchy in which the title of each object to have a higher contrast. The number of debris in each collision or explosion appears in bold but at a smaller scale to indicate their secondary importance. The explanatory text is set in a regular weight to keep the message legible at glance distance while preserving detail for closer reading.

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Rocket stage explodes in orbit
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Sputnik 1

First artificial satellite launched

NOAA-16

Defunct weather satellite breaks apart on its own
>400 debris

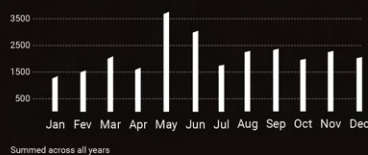
Long March 6A

Second stage of a rocket fragmented weeks after launch
>700 debris

Starlink

First batch of 60 satellites, start of mega-constellations

OBJECTS PER MONTH



OBJECTS ALONG THE YEARS



Figure 7.7: Isometric variant (angle A)

The sculpture is positioned in an isometric view because, since the experience is better enjoyed in real life, where the viewer can walk around the object and experience different points of view. Here, we wanted to capture the overall shape of the object from many angles. That is why we made many variations in the isometric view from different angles as well, so people could change a bit their perspective seeing the angles like they would in real life, we wanted to capture that feeling with the chosen pictures. We also made some side pictures so people could better see patterns that, in an isometric view, are more difficult to perceive.

Since this is a 3D visualization, it suffers from occlusion and some pattern recognition constraints, and sometimes the viewer cannot see everything that is there from a single angle. The multi-angle strategy addresses this limitation while maintaining the same consistency in layout, grid, and typographic system across the different outputs.

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When a rocket explodes or a satellite dies, their parts keep orbiting around Earth at several kilometres per second. One collision can shatter into thousands of pieces that can hit other objects and create even more debris. If we keep launching without cleaning up we will create more piles of debris orbiting Earth making space missions risky and the systems we rely on be interrupted or lost.

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First collision between two intact satellites
>2300 debris

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Operational Soviet satellite hit by untracked fragment
>300 debris

NOAA-16

Defunct weather satellite breaks apart on its own
>400 debris

Fengyun-1C

Chinese anti-satellite missile test
>3000 debris

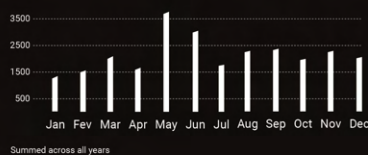
Long March 6A

Second stage of a rocket fragmented weeks after launch
>600 debris

Starlink

First batch of 60 satellites, start of mega-constellations

OBJECTS PER MONTH



OBJECTS ALONG THE YEARS



Figure 7.8: Isometric variant (angle B)

The small informative text in each infographic was chosen to tell more about the problematic we face without getting into too much detail, since this is a piece that should be readable by anyone who does not have a degree in any field of expertise. It is placed near the title block to maintain a clear reading order, and it is set in regular weight, with a high contrast against the dark background, allowing the message to be accessible at a glance without competing with the object (Figure 7.8).

Immediately below we added a compact unit note that states “Each cube represents **69 satellites**,” with “**69 satellites**” in bold and accompanied by a small circular token showing a cube that is present in the sculpture (Figure 7.9). The circle frames the cube, separating it from the background and serving as a legend key rather than decoration. This unit note is kept consistent across the set so that, whether the reader encounters an isometric, front, or side view, the meaning of the cube remains stable.

TRASH MOUNTAIN

Space is filling up, and we depend on it more than ever. Satellites make modern life possible with GPS, internet, weather and communication.

When a rocket explodes or a satellite dies, their parts keep orbiting around Earth at several kilometres per second. One collision can shatter into thousands of pieces that can hit other objects and create even more debris. If we keep launching without cleaning up we will create more piles of debris orbiting Earth making space missions risky and the systems we rely on be interrupted or lost.

Each cube represents

69 satellites



Iridium 33 × Cosmos 2251

First collision between two intact satellites
>2300 debris

Cosmos 1275

Operational Soviet satellite hit by untracked fragment
>300 debris

Nimbus 4 Upper Stage

Rocket stage explodes in orbit
>400 debris

Fengyun-1C

Chinese anti-satellite missile test
>3000 debris

Long March 6A

Second stage of a rocket fragmented weeks after launch
>700 debris

Long March 6A

Second stage of a rocket fragmented weeks after launch
>600 debris

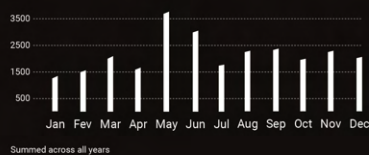
NOAA-16

Defunct weather satellite breaks apart on its own
>400 debris

Starlink

First batch of 60 satellites, start of mega-constellations

OBJECTS PER MONTH



OBJECTS ALONG THE YEARS



Figure 7.9: Isometric variant (angle C)

We also added temporal indicators to the isometric infographics, aligning them to the isometric grid to improve legibility. These indicators are shown on the grid for a more consistent reading. We omitted some of these indicators in infographics where the overall shape alone was already clear enough to reveal the patterns, such as the one that uses the front view (Figure 7.10) and the one that uses the side view (Figure 7.11). In the side view, we did not add any additional indicators because, unlike in the isometric view, the placement of labels became very cluttered, and in that angle, showing the evolution across time is more interesting than knowing exactly what happened in each year, since those specifics can be inferred when the viewer sees the other isometric infographics. We used small ticks so the reader can better understand where the indications of months and years lie, the sculpture itself does not have these indications, they can be seen only on the infographics.

The text of the months and years also follows the isometric grid, making the reading more straightforward. The text alone made it a bit confusing to determine where the columns were, as the sculpture has some irregularities and is not entirely straight (which is a good thing for the concept itself, but not for reading the data). To make this more understandable and the information more readable, we used these small ticks. The grid-aligned ticks stabilize the temporal axis against those slight geometric deviations and help preserve the mapping logic from the object to the graphic surface.

TRASH MOUNTAIN

Space is filling up, and we depend on it more than ever. Satellites make modern life possible with GPS, internet, weather and communication.

When a rocket explodes or a satellite dies, their parts keep orbiting around Earth at several kilometres per second. One collision can shatter into thousands of pieces that can hit other objects and create even more debris. If we keep launching without cleaning up we will create more piles of debris orbiting Earth making space missions risky and the systems we rely on be interrupted or lost.

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>3000 debris

Long March 6A

Second stage of a rocket fragmented weeks after launch
>700 debris

NOAA-16

Defunct weather satellite breaks apart on its own
>400 debris

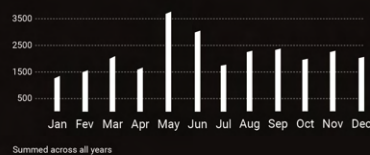
Long March 6A

Second stage of a rocket fragmented weeks after launch
>600 debris

Sputnik 1

First artificial satellite launched

OBJECTS PER MONTH



OBJECTS ALONG THE YEARS



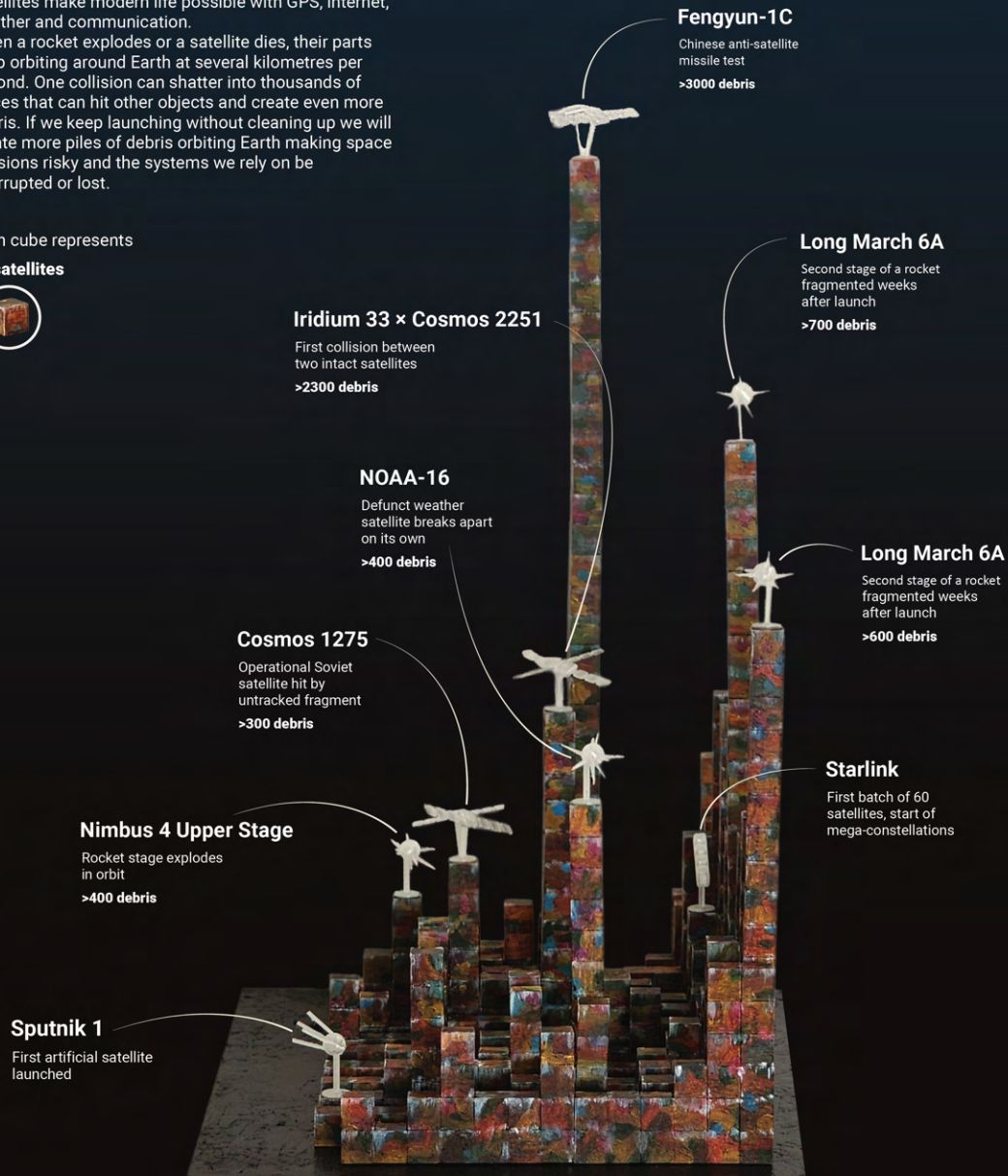
Figure 7.10: Front view Infographic

TRASH MOUNTAIN

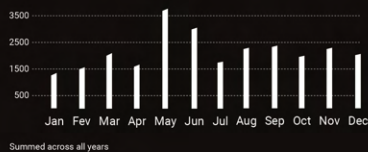
Space is filling up, and we depend on it more than ever. Satellites make modern life possible with GPS, internet, weather and communication. When a rocket explodes or a satellite dies, their parts keep orbiting around Earth at several kilometres per second. One collision can shatter into thousands of pieces that can hit other objects and create even more debris. If we keep launching without cleaning up we will create more piles of debris orbiting Earth making space missions risky and the systems we rely on be interrupted or lost.

Each cube represents

69 satellites



OBJECTS PER MONTH



OBJECTS ALONG THE YEARS



Figure 7.11: Side view Infographic

We also added more information: the same information that is on the sculpture is translated into 2D graphics with bar charts that can be seen below the sculpture, for a better reading and better understanding of the data.

Since the sculpture is an object that also gets attention for the marks and history of objects in space debris, the graphics behind it make the information crystal clear for understanding, without the object's information density getting in the way.

The graphics are two, one for the launches per month and one for the launches along the years. They have a different scale from the sculpture because we had to use the same scale for both graphics. We also used a small dotted line so it was clearer to read the scale of the graphics. Only one scale indication is used on the left, what separates the two graphics is the spacing between them, but they represent different aspects of the same data. For the bars, we also made them slightly inclined at the top, although it was not absolutely necessary, this gave them a more interesting shape than just a rectangle, and we think it is more contemporary, which suits the space debris theme. There are also indications of the months and two indications of the year. We left it like this because it looked more interesting to emphasize the evolution instead of listing all years, a complete enumeration would have caused conflicts and too much visual pollution.

7.7 Posters

The posters created followed a pattern used in many campaigns: a short headline in the same font as the infographics to call attention to the subject matter, a photograph, and a small explanatory text. The explanatory text clarifies what the problem we face is. Besides the infographic, that is what we want to call people's attention to because, if this were visible in everyday life, people would probably be more concerned about it, but since this is perceived as a "faraway problem," many do not even know it exists.

The pictures play with the different perspectives the sculpture can have depending on how you look at it: from above with the line "What comes up, might never come down" (Figure 7.12), from the front with "This isn't a city, it's orbital debris" (Figure 7.13), from the side with "We're building skyscrapers in the sky made of junk" (Figure 7.14), with close-ups using "You're looking at six decades of space junk" (Figure 7.15) and playing with perspective inside the sculpture using "Space is running out of space" (Figure 7.16). By calling people's attention first to the phrase and then to the image, and later leading them to read the text, the poster reframes the photograph with the necessary context. The image alone may not convey the problem if the viewer lacks context, by providing that context, the reading changes. With some images, this is more immediate, while with others, it is more subtle, and the headline does more work.

WHAT COMES UP... MIGHT NEVER COME DOWN



Earth's orbit is filling up, and we depend on it more than ever. Satellites make modern life possible with GPS, internet, weather and communication.

When a rocket explodes or a satellite stop working, their parts keep orbiting Earth at very high speeds increasing the risk of collision. If we keep launching without cleaning up we will create more piles of debris making space missions risky and the systems we rely on be interrupted or lost.

Figure 7.12: Top view Poster

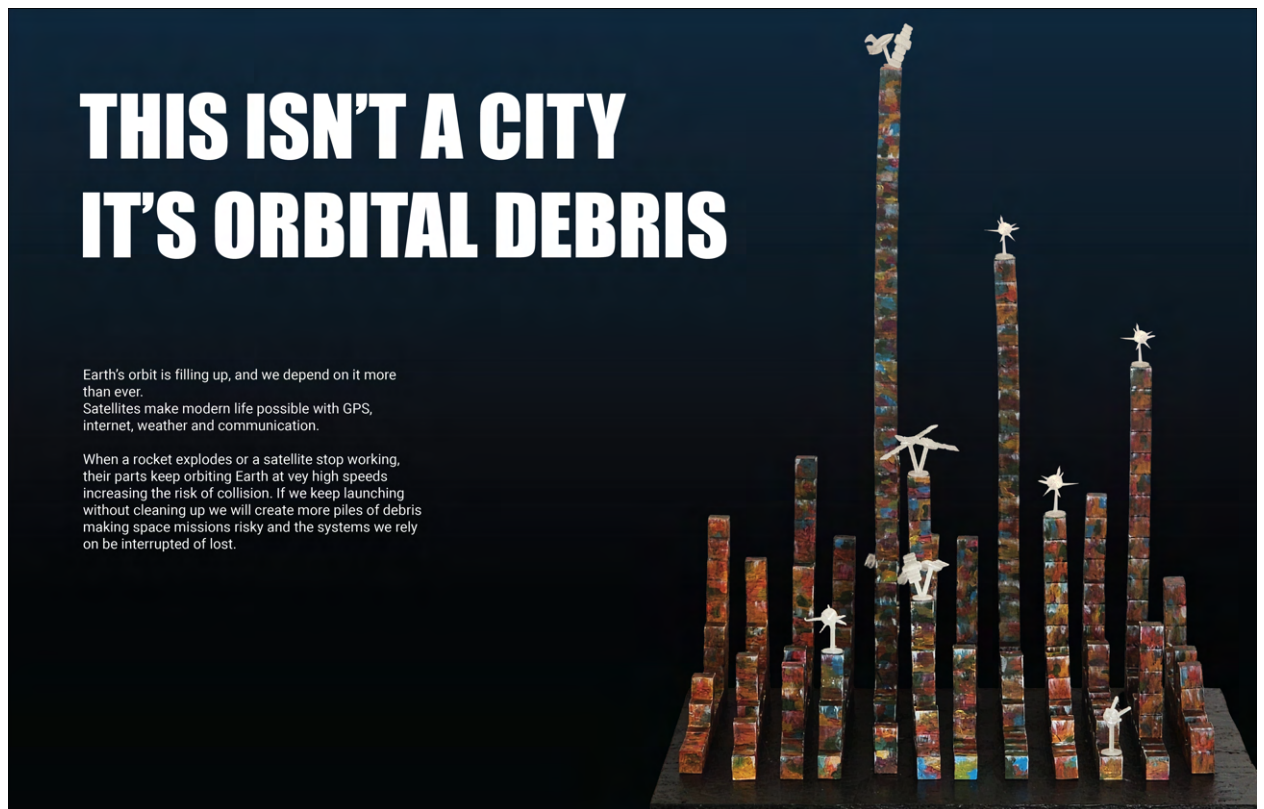


Figure 7.13: Front view Poster

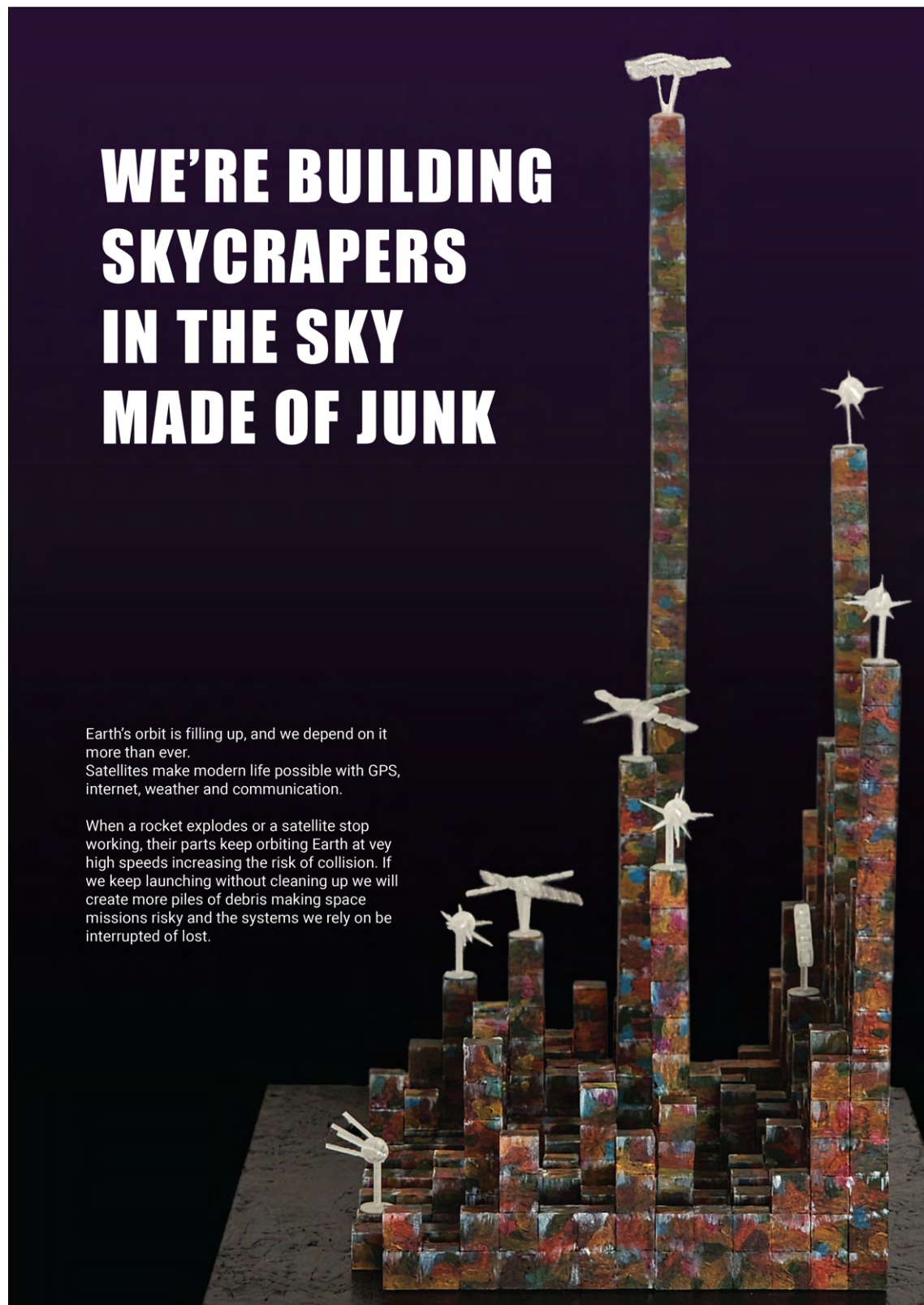


Figure 7.14: Side view Poster

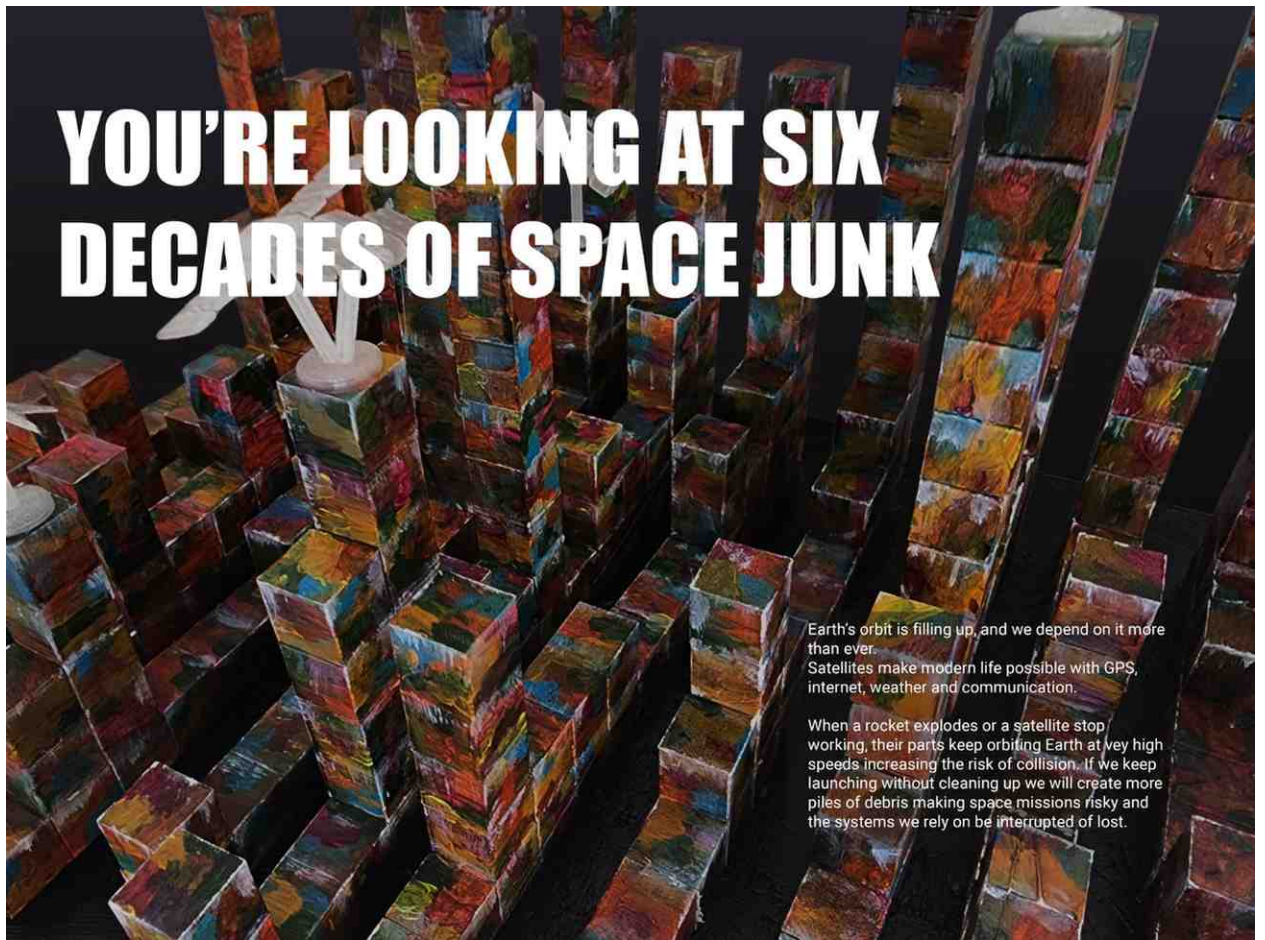


Figure 7.15: Close up Poster



Figure 7.16: Enclosed Poster

By the end of it, we placed the posters in mockups to show how they could look in real contexts (Figure 7.17). Since many awareness campaigns use bus stops to reach everyday viewers, we placed them in bus stops (Figure 7.18 and figure 7.19) and also in billboards (Figure 7.21 and figure 7.22), and we also made a composition where we showed some of them next to each other (Figure 7.20). The goal was to present them as a coherent family of posters, showing the same

problem in different ways, with varying images and phrases to capture people's attention, and then explain the problem. They all share the same explanatory text, typography and visual language with the gradients remaining the same of the infographics.



Figure 7.17: Poster on Bus Stop



Figure 7.18: Poster on Bus Stop



Figure 7.19: Poster on Bus Stop

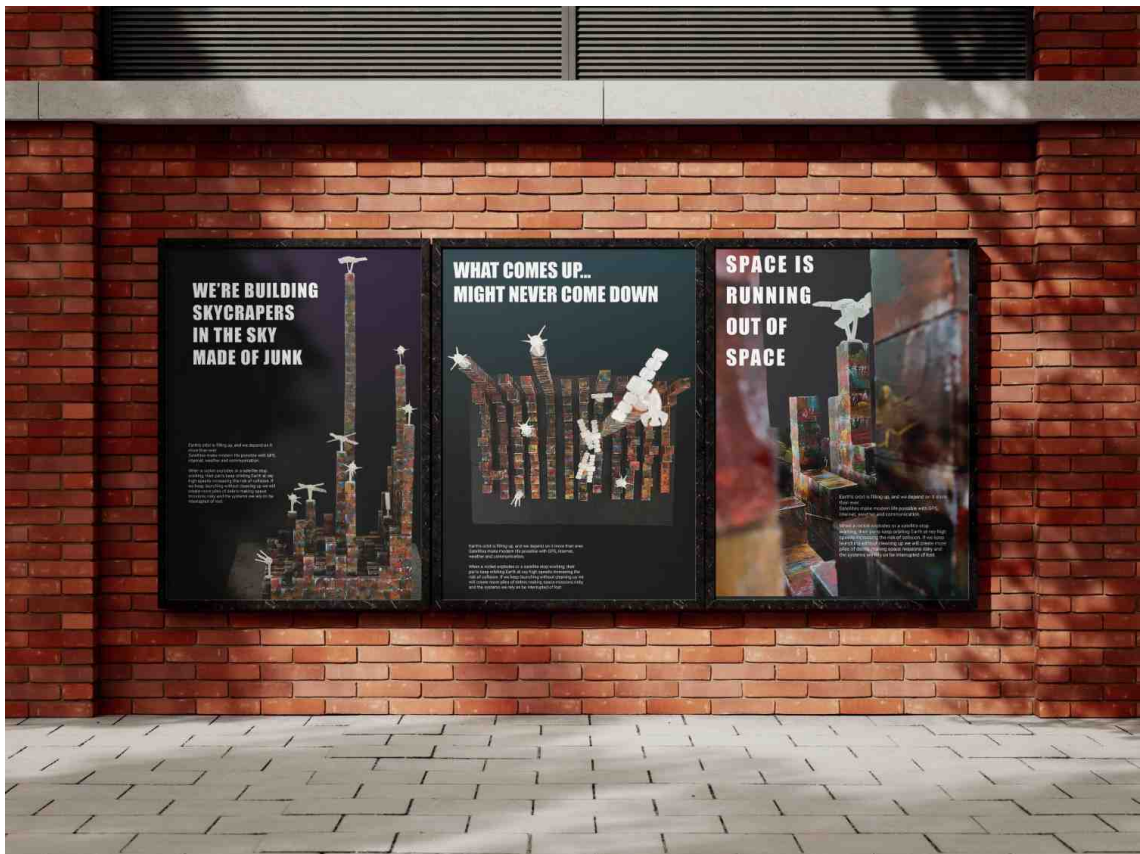


Figure 7.20: Mockup of posters created



Figure 7.21: Billboard adaptation



Figure 7.22: Alternative Billboard

On a more playful note we also added stickers with the phrase “Houston, we have a trash problem,” using a similar image to one of the posters. Since the target audience are high school students, we wanted to speak in a language closer to their media habits without making everything overly informal. The stickers serve as portable elements of the campaign, allowing them to circulate beyond formal poster placements.

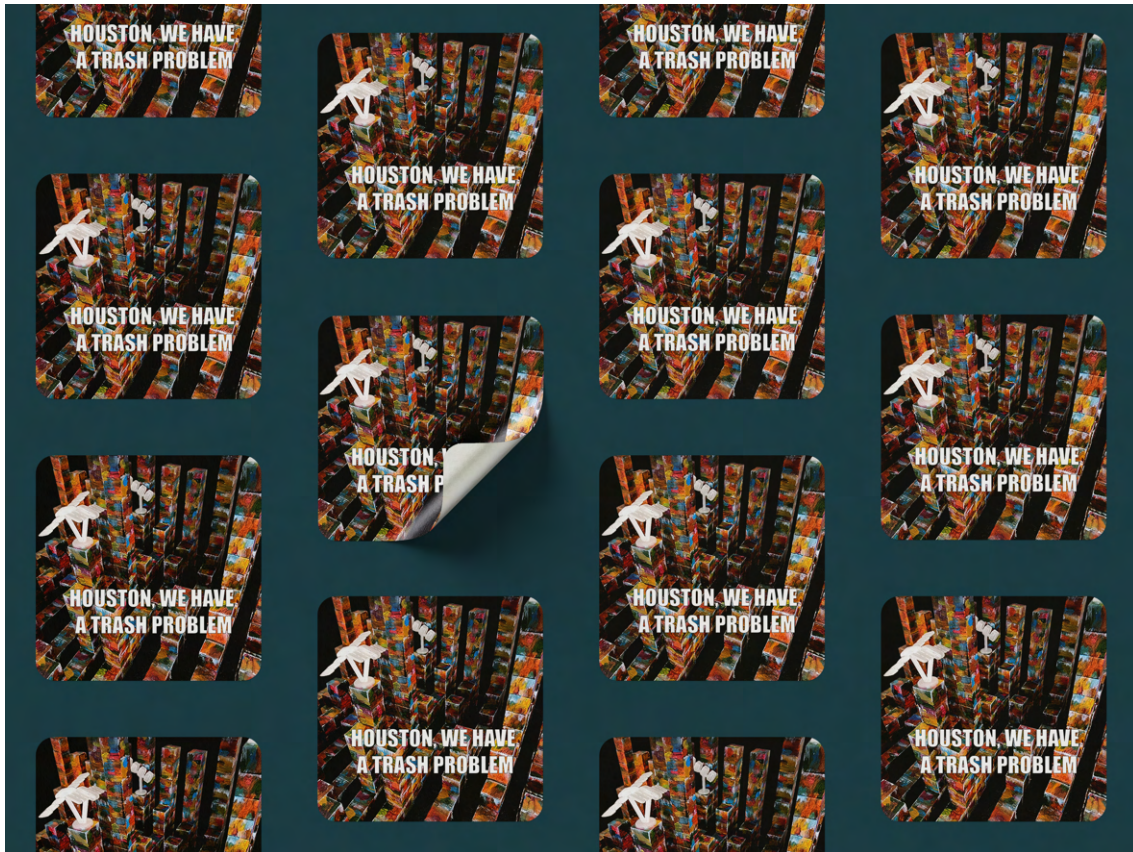


Figure 7.23: Stickers

We also created a few tote bags featuring the phrase “Carrying Space Trash”, using the object as a means to convey both the information encoded in the sculpture and its symbolic representation. The aim was to create a portable, everyday artifact that extends the campaign beyond the exhibition settings and speaks to our target audience in a more casual context. We designed two variants: one with a closer look at the sculpture, allowing for better detail visibility, and another showing the entire sculpture. The typography and palette follow the campaign system, so recognition is immediate across formats.



Figure 7.24: Tote Bag



Figure 7.25: Tote Bag variation 1

7.8 Reflection

The campaign remains consistent across all materials, maintaining the same typography, color palette, and hierarchy. This creates a consistency across all materials that can be easily recognizable as part of the same narrative.

Regarding the effectiveness of the infographics, the darker gradients and the black lower field improved contrast, hid the base, and made small ticks and captions more legible. The typographic hierarchy matches how viewers scan the panel and keeps the message clear at multiple distances. The isometric grid, with month and year ticks, stabilized temporal reading despite minor physical irregularities in the sculpture. The use of photographs from multiple angles combined with two bar charts balanced the object's form with an accurate interpretation.

In the context of the posters, the less successful aspects concern their reliance on the headline and the short explainer text to disclose that the sculpture may represent data. Without the text, several photographs can be read simply as beautiful images, as the public lacks context on what the sculpture really represents. This results from a deliberate choice that prioritizes impact and fast comprehension at a distance over detail, but it reduces the autonomy of the image.

The original plan included creating renders in the Informatic Engineer Department (DEI) to show the campaign in its context, to see how the objects and graphic materials would look in the actual spaces where the campaign could take place. With several unforeseen setbacks in fabrication and iteration, there was not enough time to execute those renders on schedule.

Protecting the scope close to the deadline required focusing on finishing the physical object and the core set of visual materials. As future work, we could have two improvements: renders or photographs of the object with posters in DEI to validate scale, and second, short video reels (vertical, 10–30s) that reuse the isometric variations and close-ups with captions for Instagram/TikTok to better reach a younger audience.

Chapter 8

Conclusion

This project moved from open exploration to a set of deliberate choices about how to make orbital-debris data readable in physical form. The exploration in Chapter 5 was essential for that shift. It established the practical ground: what the dataset could support after cleaning and filtering, which mappings were even legible when translated from the screen, what information should be conveyed, which materials and scales were realistic, as well as which ideas looked promising but collapsed under the constraints of fabrication or clarity.

The Orbital Debris Iris demonstrated that mapping growth to diameter can be an interesting concept, but also revealed how tolerances, friction, and torque quickly set the limits of what can be built and driven within the available resources. The Speed Track clarified how relative orbital periods and speeds can be compared through a gear mechanism and traced. However, the accuracy demands of the build and the alignment of parts prevented it from progressing beyond the concept and render stage. These outcomes were not intentional failures, they were the steps needed to understand which forms carry the message and which do not under real constraints.

From that process, we decided to center the campaign on the Trash Mountain sculpture. The metaphor is simple and effective for a first-time audience: accumulation has mass, height, and permanence. The chosen mapping keeps peaks visible while maintaining the object's fabricability and transportability. Even without formal user tests, the object provides some face validity: from a distance, the silhouette conveys growth over time, and up close, it is possible to see the marks related to collisions and launches. The painting and finishing choices support the metaphor without hiding the structure.

Some planned parts of the work were not completed, as there was no formal user testing, and the motorization of the iris and the full build of the Speed Track were not completed due to time and budget constraints, as well as fabrication challenges that were larger than anticipated. These limits should be considered when planning projects of this scope, especially when electronics, tight tolerances, and moving parts are involved.

Future work follows directly from these gaps. The Orbital Debris Iris can be com-

pleted with redesigned joints, lower-friction materials or bearings, and a higher-torque drive sized against measured loads. The Speed Track can be finalized with controlled dimensions, a stiffer frame, and calibrated motion, so that period and speed comparisons are shown reliably on the vinyl.

Regarding the final object, improvements that can be made could be to create renders in DEI to validate scale and placement of the objects and materials, and to create new ways of communicating using the format of short reels on platforms such as Instagram and TikTok that better reach a younger audience. Most importantly, the campaign should also be evaluated in terms of its intended audience and effectiveness.

Across this project, making and creating were how we moved forward. Experimenting with different methods and materials revealed where the data speaks clearly in physical form and where it becomes noise. Practical issues such as precision, friction and time didn't end the conversation, they shaped it, forging a path toward a simpler, more readable choice. What remains is a piece that carries the message without relying on perfect conditions, and a record of the paths that led to this decision. That is the value of experimentation: it turned uncertainty into criteria, and criteria into a coherent outcome. The evolution from many ideas to a single central object was necessary to achieve this.

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Appendices

Appendix A

Appendix

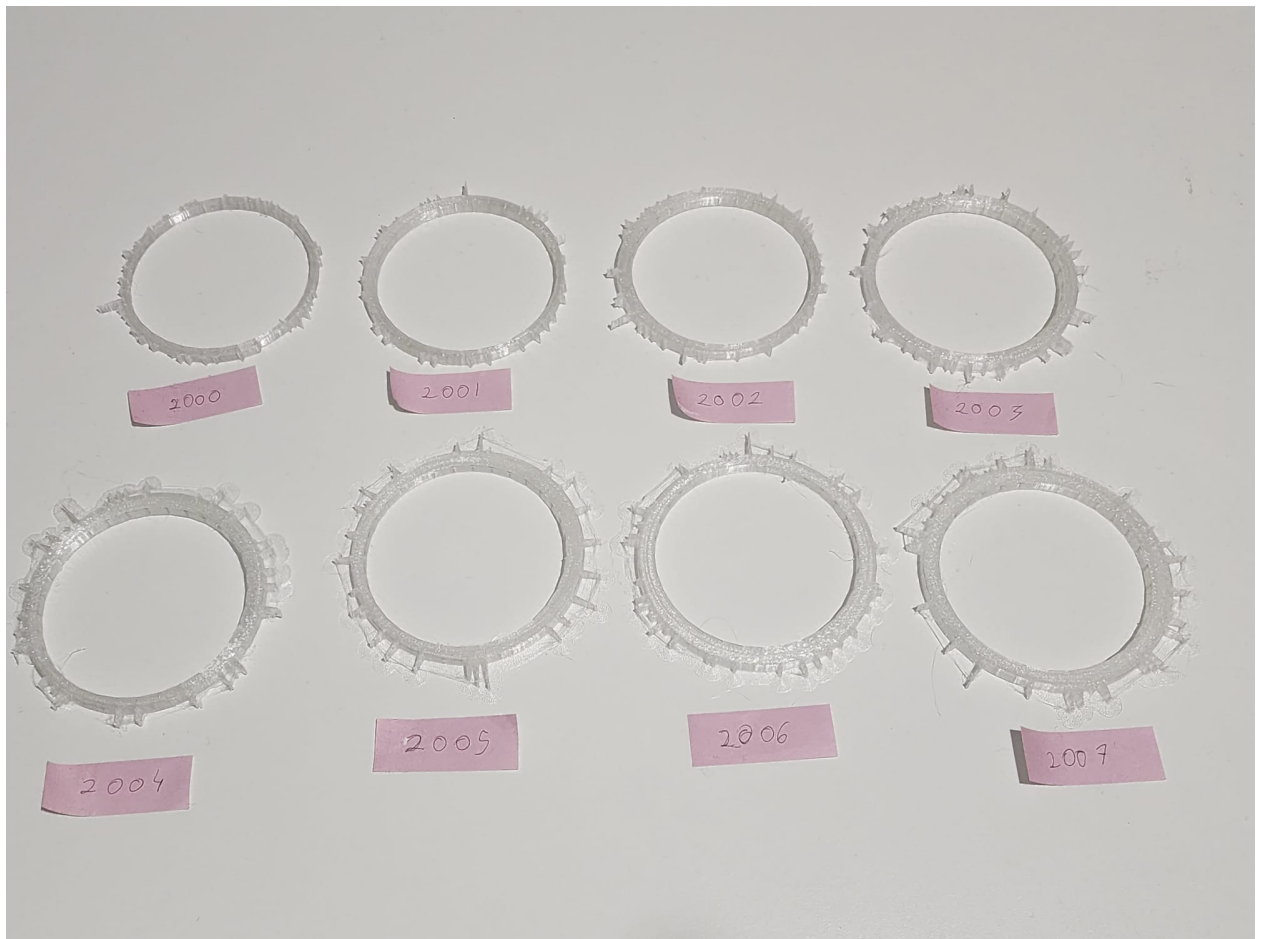


Figure A.1: Bracelets from 2000 to 2007



Figure A.2: Bracelets from 2008 to 2015



Figure A.3: Bracelets from 2016 to 2022

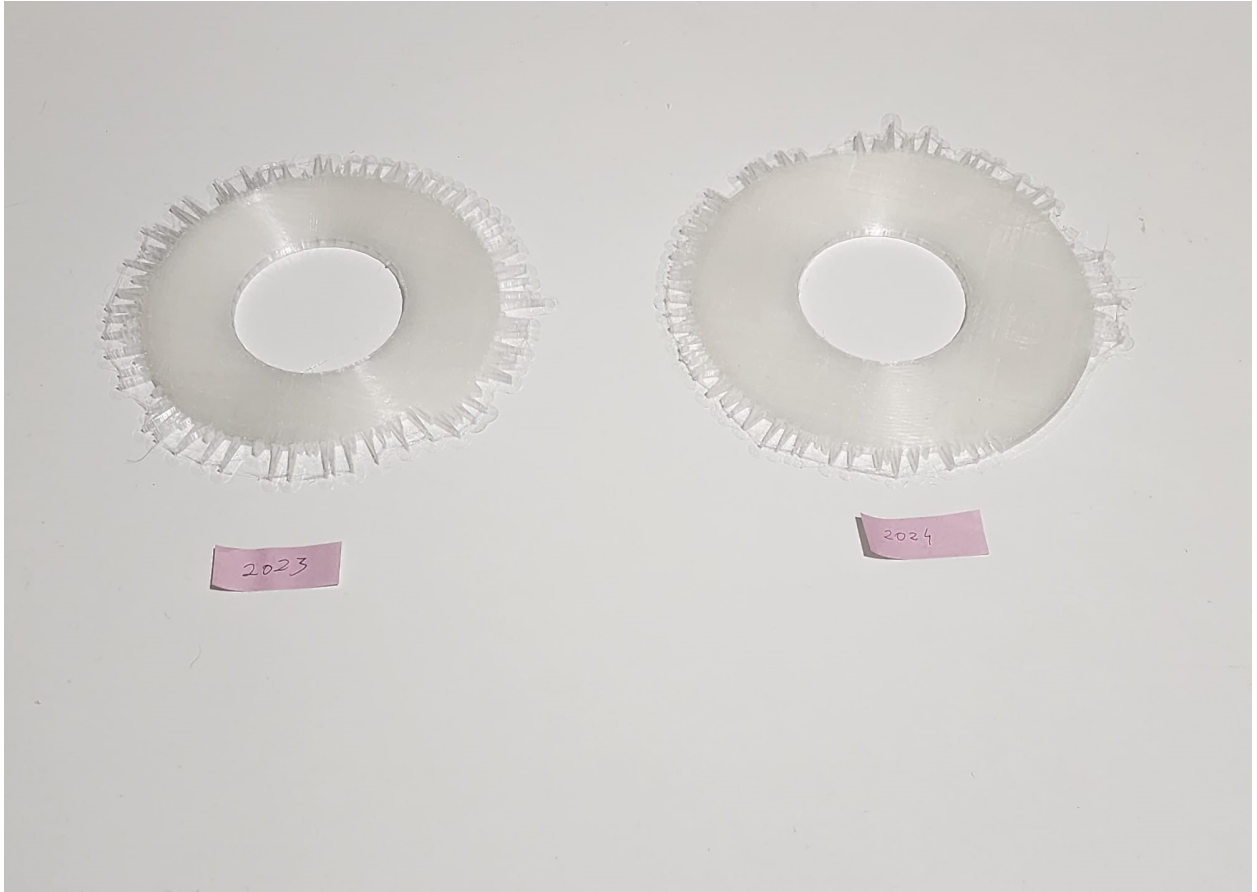


Figure A.4: Bracelets from 2023 to 2024

A.0.1 Speed Track Math

The fluorescent vinyl moves at constant speed v_{vinyl} , so $x(t) = v_{\text{vinyl}}t$, and the printed trace is the spatial sine

$$y_j(x) = R_j \sin\left(\frac{2\pi}{\lambda_j}x + \phi_j\right), \quad \lambda_j = v_{\text{vinyl}} T_{\text{mech},j}. \quad (\text{A.1})$$

Here λ_j is the wavelength on the vinyl and $T_{\text{mech},j} = 2\pi/\omega_j$ is the mechanical period of disc j . Each object type is plotted on its own lane.

In the Python bubble chart, the bubble *area* is proportional to the average orbital period in that region:

$$A_j^{\text{chart}} = s_A \bar{T}_j, \quad A_j^{\text{chart}} \leq A_{\text{max}}, \quad (\text{A.2})$$

with chart scale s_A and cap A_{max} . The equivalent chart radius is

$$r_j^{\text{chart}} = \sqrt{\frac{A_j^{\text{chart}}}{\pi}} = \sqrt{\frac{s_A}{\pi}} \sqrt{\bar{T}_j}. \quad (\text{A.3})$$

Choosing a single physical size scale k_R (mm per chart unit), the real disc radius that also equals the traced amplitude is

$$R_j = k_R r_j^{\text{chart}}, \quad D_j = 2R_j, \quad (\text{A.4})$$

so

$$R_j \propto \sqrt{\bar{T}_j}. \quad (\text{A.5})$$

Compressing time by a constant factor $\alpha \ll 1$ and setting the mechanical period to

$$T_{\text{mech},j} = \alpha \bar{T}_j, \quad \omega_j = \frac{2\pi}{T_{\text{mech},j}} = \frac{2\pi}{\alpha \bar{T}_j}. \quad (\text{A.6})$$

Substituting (A.6) into (A.1) gives the wavelength on vinyl:

$$\lambda_j = v_{\text{vinyl}} \alpha \bar{T}_j \propto \bar{T}_j. \quad (\text{A.7})$$

We can see that the longer orbital period = slower oscillation

Combining (A.5) and (A.7),

Amplitude $R_j \propto \sqrt{\bar{T}_j}$ and Wavelength $\lambda_j \propto \bar{T}_j$.

(A.8)

Using the orbital period can be a valid approximation for the angular speed (but not linear speed). For near-circular orbits we only need two standard facts (semi-major axis a , gravitational parameter μ),

$$T = 2\pi \sqrt{\frac{a^3}{\mu}}, \quad v = \sqrt{\frac{\mu}{a}}. \quad (\text{A.9})$$

Combining them (eliminating a): from $T \propto a^{3/2}$ we get $a \propto T^{2/3}$, plugging this in $v = \sqrt{\mu/a}$ gives

$$v \propto T^{-1/3}. \quad (\text{A.10})$$

Using (A.5), $R_j \propto \sqrt{T}$ (area $\propto T$), so $T \propto R_j^2$ and

$$v \propto R_j^{-2/3}. \quad (\text{A.11})$$

So, *longer period $\Rightarrow$ lower orbital speed*, visually this appears as a taller and more widely spaced wave.

movimento harmônico simples

$$\frac{d^2x}{dt^2} = a = \text{constante}$$

↳ integrando ambos os membros em relação a t temos a lei de variação da velocidade

$$\int_0^t \frac{d^2x}{dt^2} dt = \left[\frac{dx}{dt} \right]_0^t \Rightarrow \underbrace{v(t) - v(0)}_{v_0} = a \int_0^t dt = at$$

$$v(t) = \frac{dx}{dt} = v_0 + at$$

v_0 é a velocidade inicial, e integrar novamente em relação a t ,

$$\int_0^t \frac{dx}{dt} dt' = [x]_0^t$$

$$x(t) - \underbrace{x(0)}_{x_0} = v_0 \int_0^t dt' + a \int_0^t t' dt'$$

$$v_0 t + \frac{at^2}{2}$$

$$x(t) = x_0 + v_0 t + \frac{at^2}{2}$$

$$\begin{cases} x(0) = x_0 \\ \frac{dx}{dt}(0) = v(0) = v_0 \end{cases}$$

$$x(t) = A + Bt + \frac{at^2}{2}$$

Figure A.5: Harmonic oscillator

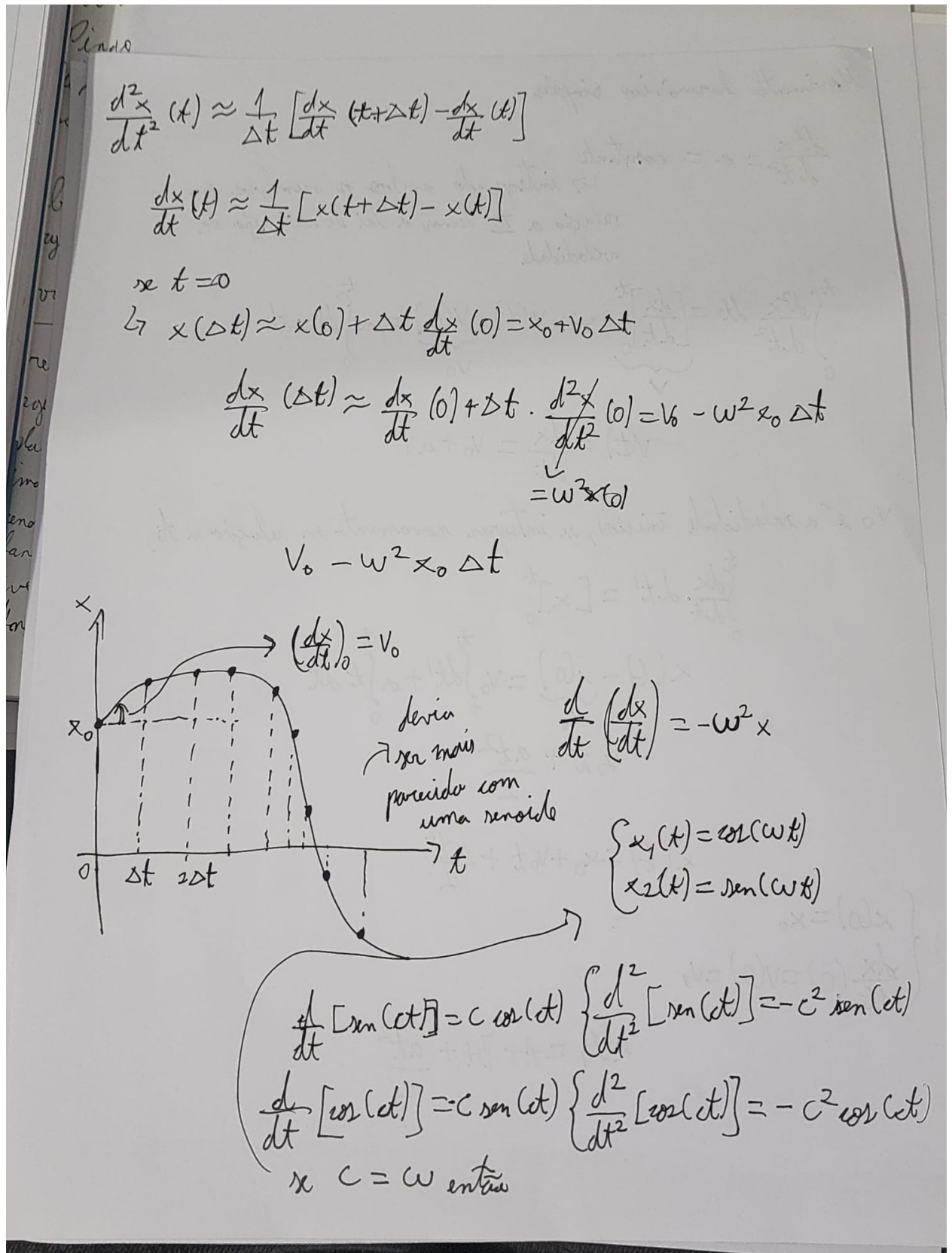


Figure A.6: Harmonic oscillator

O led preso no círculo de raio R_j que gira a velocidade constante ω_j

Ângulo $\Rightarrow \theta_j(t) = \omega_j t + \phi_j$

O led vai fazer movimento circular uniforme, a projeção no eixo vertical vai ser um seno em função do tempo:

$$y_j(t) = R_j \sin(\omega_j t + \phi_j)$$

A amplitude $|y_j(t)| \leq R_j \Rightarrow R_j(\text{mm})$

quando aumenta pra 2π a forma se repete

$$\hookrightarrow T_{\text{med } j} = \frac{2\pi}{\omega_j}$$

$$\left. \begin{array}{l} R_j \rightarrow \text{mm} \\ \omega_j \rightarrow \text{rad/s} \end{array} \right\} y_j \Rightarrow \text{mm/s}$$

O vinil teoricamente vai se movimentar a velocidade constante

$$V_{\text{vinyl}} \Rightarrow \text{mm/s}$$

$$x(t) = V_{\text{vinyl}} t$$

$$t = \frac{x}{V_{\text{vinyl}}}$$

substituindo em $y_j(t)$

$$y_j(x) = R_j \sin\left(\omega_j \frac{x}{V_{\text{vinyl}}} + \phi_j\right)$$

$$R_j \sin\left(\frac{2\pi}{\lambda_j} x + \phi_j\right)$$

Figure A.7: Math for the gear mechanism

or a line for form Rings loc → 29.95 14.98
 $\lambda_j = \frac{2\pi V_{ring}}{w_j} \Rightarrow V_{ring} T_{mech_j}$
 $\bar{T}_j$ codificado na área do círculo físico
 $A_{dent} = \pi (r_j^{dent})^2$
 $S_A \rightarrow$ scale para converter o período médio em área em pixels:
 $A_{j_i}^{dent} = S_A \bar{T}_{j_i}$
 $S_A \rightarrow \text{px}^2$
 $A_{max} = \pi r_{max}^2$
 $S_A = \frac{A_{max}}{\bar{T}_{max}} = \frac{\pi r_{max}^2}{\bar{T}_{max}}$
 $A_{j_i}^{dent} = S_A \bar{T}_{j_i} \Rightarrow r_j^{dent} = \sqrt{\frac{A_{j_i}^{dent}}{\pi}}$
 $\sqrt{\frac{S_A}{\pi}} \cdot \sqrt{\bar{T}_{j_i}}$
 $r_{max} \sqrt{\frac{\bar{T}_{j_i}}{\bar{T}_{max}}}$
 Aplicando uma escala física $K_R (\text{mm/px})$
 $R_{j_i} = K_R r_j^{dent}$
 $K_R = \sqrt{\frac{S_A}{\pi}} \cdot \sqrt{\bar{T}}$
 logo $R_{j_i} \propto \sqrt{\bar{T}_{j_i}}$

Figure A.8: Math for the gear mechanism

Usando um fator de compressão $\alpha \ll 1$

$$T_{mech j} = \alpha \bar{T}_j \rightarrow \text{por definição}$$

$$\omega_j = \frac{2\pi}{T_{mech j}} \Rightarrow \omega_j = \frac{2\pi}{\alpha \bar{T}_j}$$

$$\lambda_j = v_{ring} T_{mech j}$$

substituindo $T_{mech j} = \alpha \bar{T}_j$

$$\lambda_j = v_{ring} \alpha \bar{T}_j$$

$$\lambda_j = \frac{2\pi v_{ring}}{\omega_j} \quad \text{já que } T_{mech} = \frac{2\pi}{\omega}$$

$$\frac{\lambda_i}{\lambda_k} = \frac{\bar{T}_i}{\bar{T}_k}$$

$$\omega_{min} \leq \frac{2\pi}{\alpha \bar{T}_j} \leq \omega_{max} \quad \forall j$$

$$\bar{T}_{min} \text{ e } \bar{T}_{max}$$

$$\frac{2\pi}{\omega_{max} \bar{T}_{min}} \leq \alpha \leq \frac{2\pi}{\omega_{min} \bar{T}_{max}}$$

$$T_{mech j} = \alpha \bar{T}_j$$

$$\omega_j = \frac{2\pi}{T_{mech j}} = \frac{2\pi}{\alpha \bar{T}_j}$$

Figure A.9: Math for the gear mechanism

derivando y em relação a x :

$$\frac{dy_j}{dx} = \frac{2\pi R_j}{\lambda_j} \cos\left(\frac{2\pi}{\lambda_j} x + \phi_j\right)$$

$$\left|\frac{dy_j}{dx}\right|_{\max} = \frac{2\pi R_j}{\lambda_j}$$

como $R \propto \sqrt{T_j}$ e $\lambda_j \propto T_j$

$$\left|\frac{dy_j}{dx}\right|_{\max} \propto \frac{\sqrt{T_j}}{T_j} = T_j^{-1/2}$$

Períodos muito longos geram inclinações um pouco menores, provavelmente não é necessário por isso na tese

Para órbitas quase circulares:

$$T = 2\pi \sqrt{\frac{a^3}{\mu}} \quad V = \sqrt{\frac{\mu}{a}}$$

Eliminando a em T :

Isolando

$$a^3 = \mu \left(\frac{T}{2\pi}\right)^2$$

$$a = \mu^{1/3} \left(\frac{T}{2\pi}\right)^{2/3}$$

$$V = \frac{\sqrt{\mu}}{\sqrt{a}} = \mu^{1/2} \left[\mu^{1/3} \left(\frac{T}{2\pi}\right)^{2/3} \right]^{-1/2}$$

$$= \mu^{1/2 - 1/6} (2\pi)^{1/3} T^{-1/3} = (2\pi \mu)^{1/3} T^{-1/3}$$

$$V \propto T^{-1/3}$$

Figure A.10: Math for the gear mechanism

A.0.2 Pictures



Figure A.11: Picture



Figure A.12: Picture



Figure A.13: Picture



Figure A.14: Picture



Figure A.15: Picture



Figure A.16: Picture

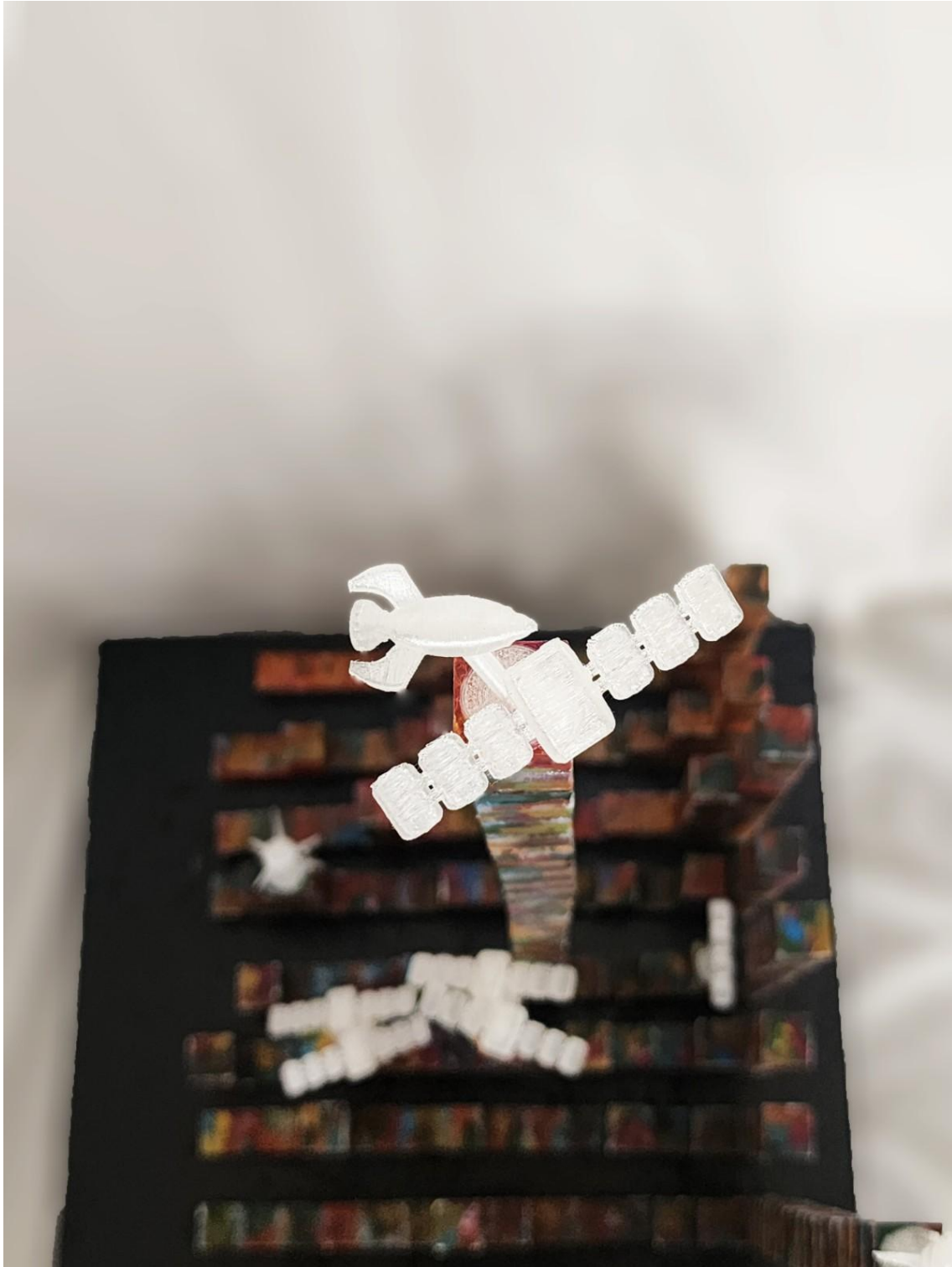


Figure A.17: Picture



Figure A.18: Picture



Figure A.19: Picture



Figure A.20: Picture



Figure A.21: Picture



Figure A.22: Picture



Figure A.23: Picture



Figure A.24: Picture



Trash Mountain

Objects launched into space along the years
blablablaaaaaaaaa, balh, blah Objects launched into space along the years blablablaaaaaaaaa, balh, blah, Objects launched into space along the years blablablaaaaaaaaa, balh, blah Objects launched into space along the years blablablaaaaaaaaa, balh, blah Objects launched into space along the years blablablaaaaaaaaa, balh, blah Objects launched into space along the years blablablaaaaaaaaa, balh, blah

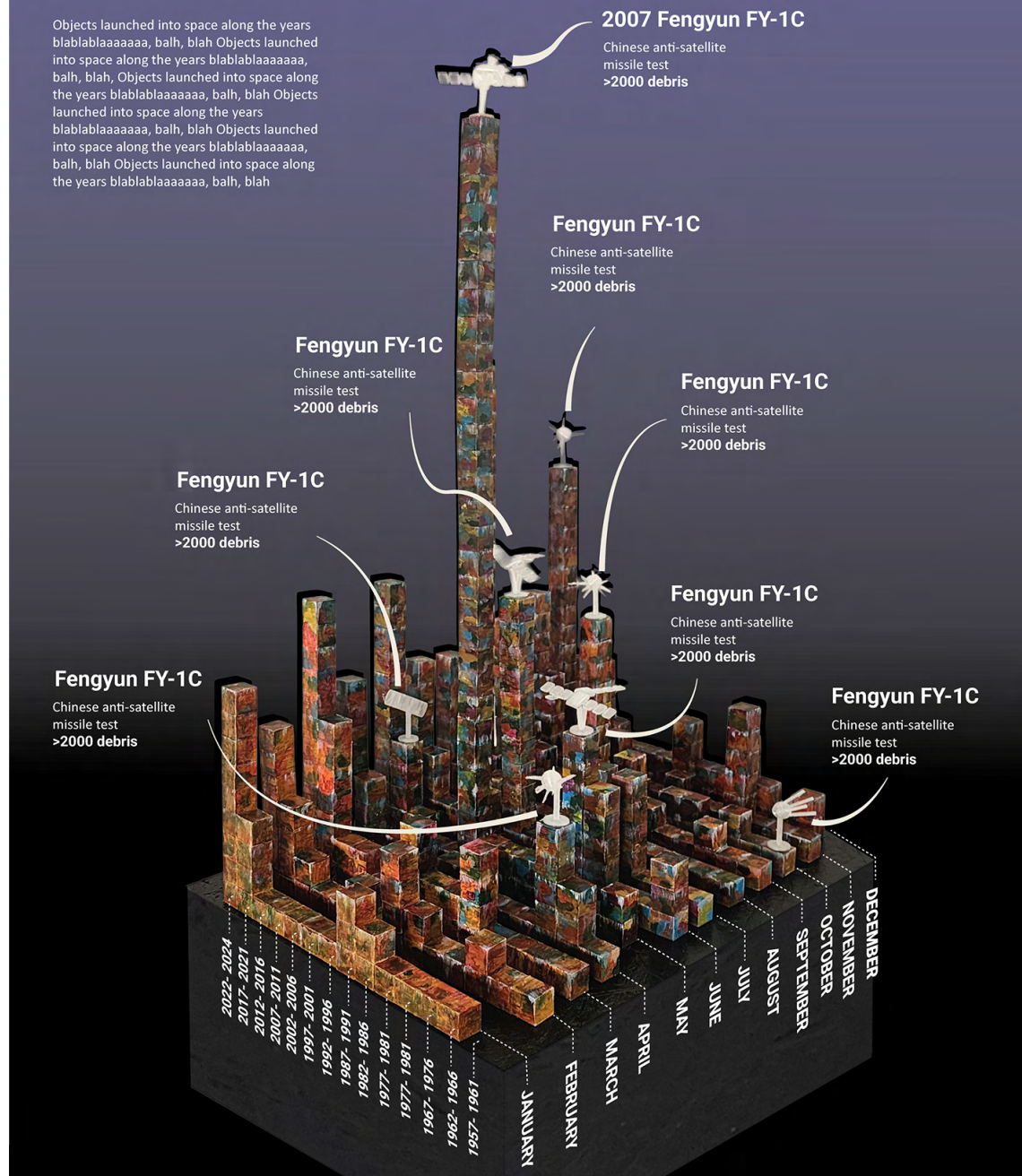


Figure A.26: Infographic Layout experience

200

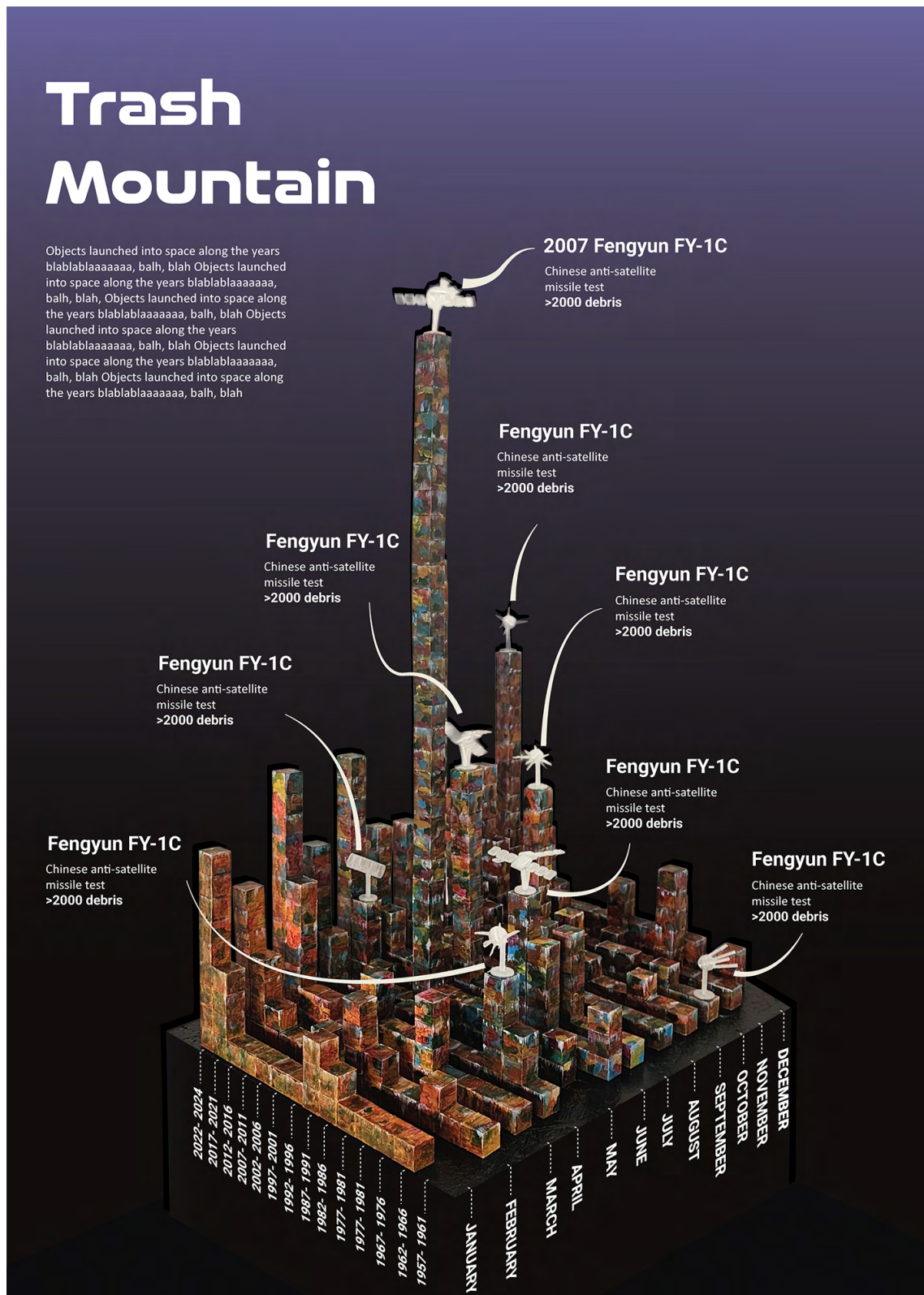


Figure A.28: Infographic Layout experience

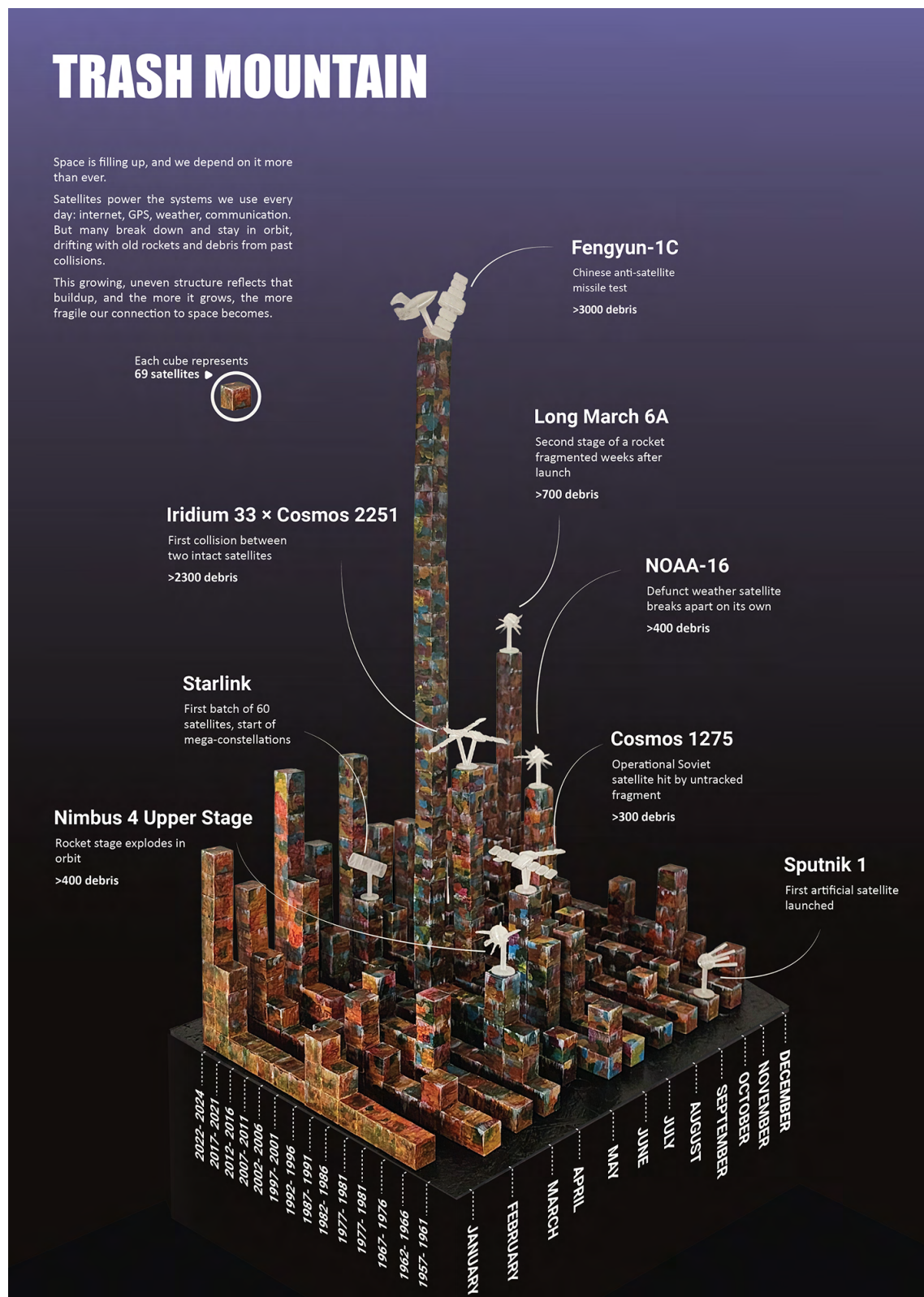


Figure A.29: Infographic Layout experience

TRASH MOUNTAIN

Space is filling up, and we depend on it more than ever.

Satellites power the systems we use every day: internet, GPS, weather, communication. But many break down and stay in orbit.

Each cube represents
69 satellites



Fengyun-1C

Chinese anti-satellite
missile test
>3000 debris

Long March 6A

Second stage of a rocket
fragmented weeks after
launch
>700 debris

Iridium 33 × Cosmos 2251

First collision between
two intact satellites
>2300 debris

NOAA-16

Defunct weather satellite
breaks apart on its own
>400 debris

Starlink

First batch of 60
satellites, start of
mega-constellations

Cosmos 1275

Operational Soviet
satellite hit by untracked
fragment
>300 debris

Nimbus 4 Upper Stage

Rocket stage explodes in
orbit
>400 debris

Sputnik 1

First artificial satellite
launched

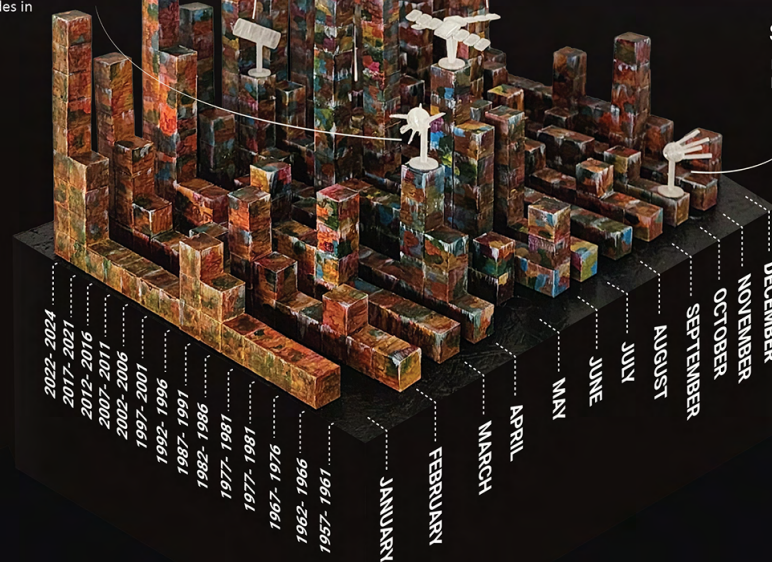


Figure A.30: Infographic Layout experience

TRASH MOUNTAIN

Space is filling up, and we depend on it more than ever. Satellites make modern life possible with services such as GPS, internet, weather and communication. When a rocket explodes or a satellite dies, fragments keep orbiting around Earth at several kilometres per second. One collision can shatter into thousands of pieces that can hit more objects and create even more debris. If we keep launching without cleaning up we will create more piles of debris orbiting Earth making space missions risky and the systems we rely on be interrupted or lost.

Each cube represents
69 satellites

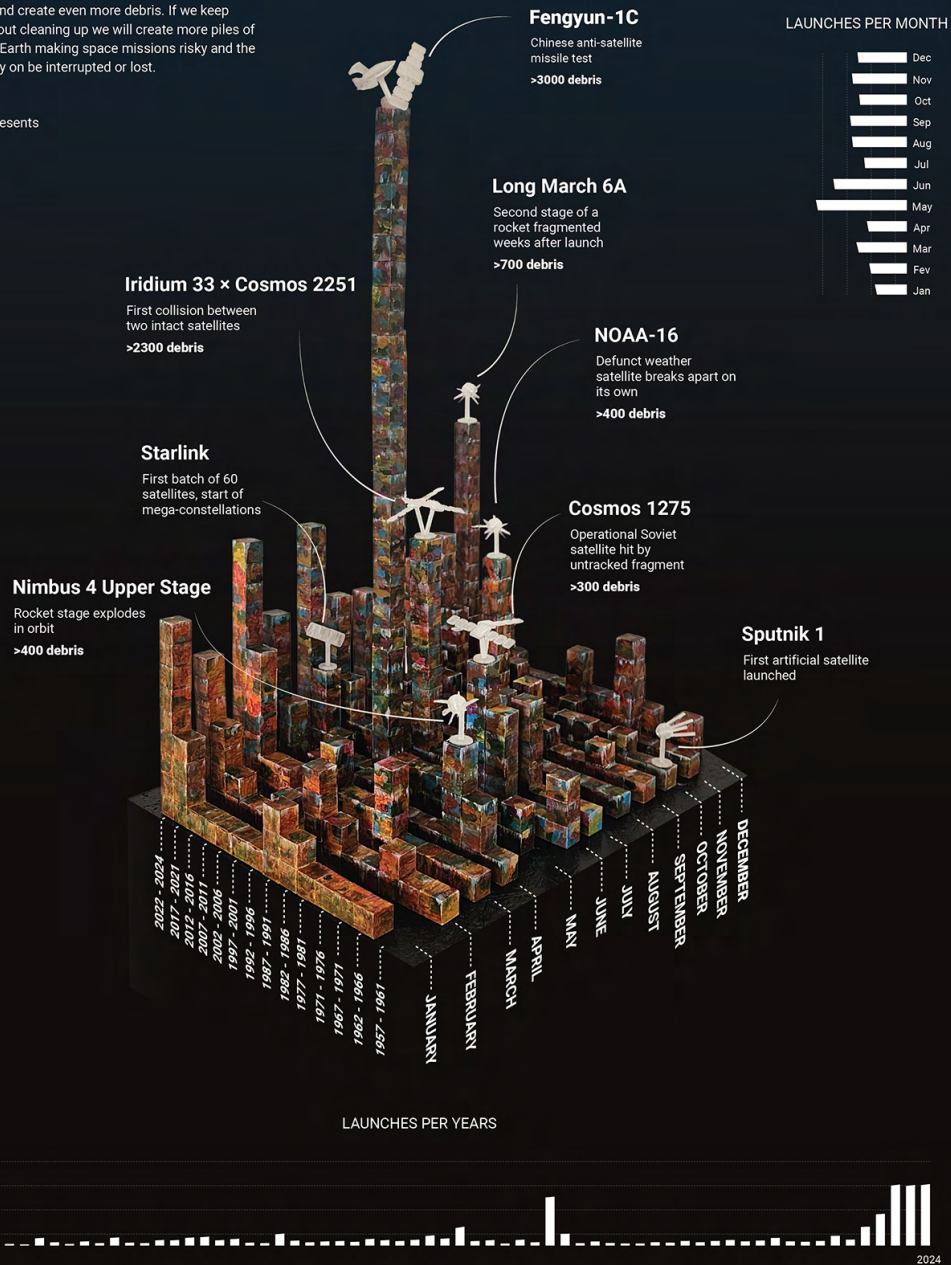


Figure A.31: Infographic Layout experience

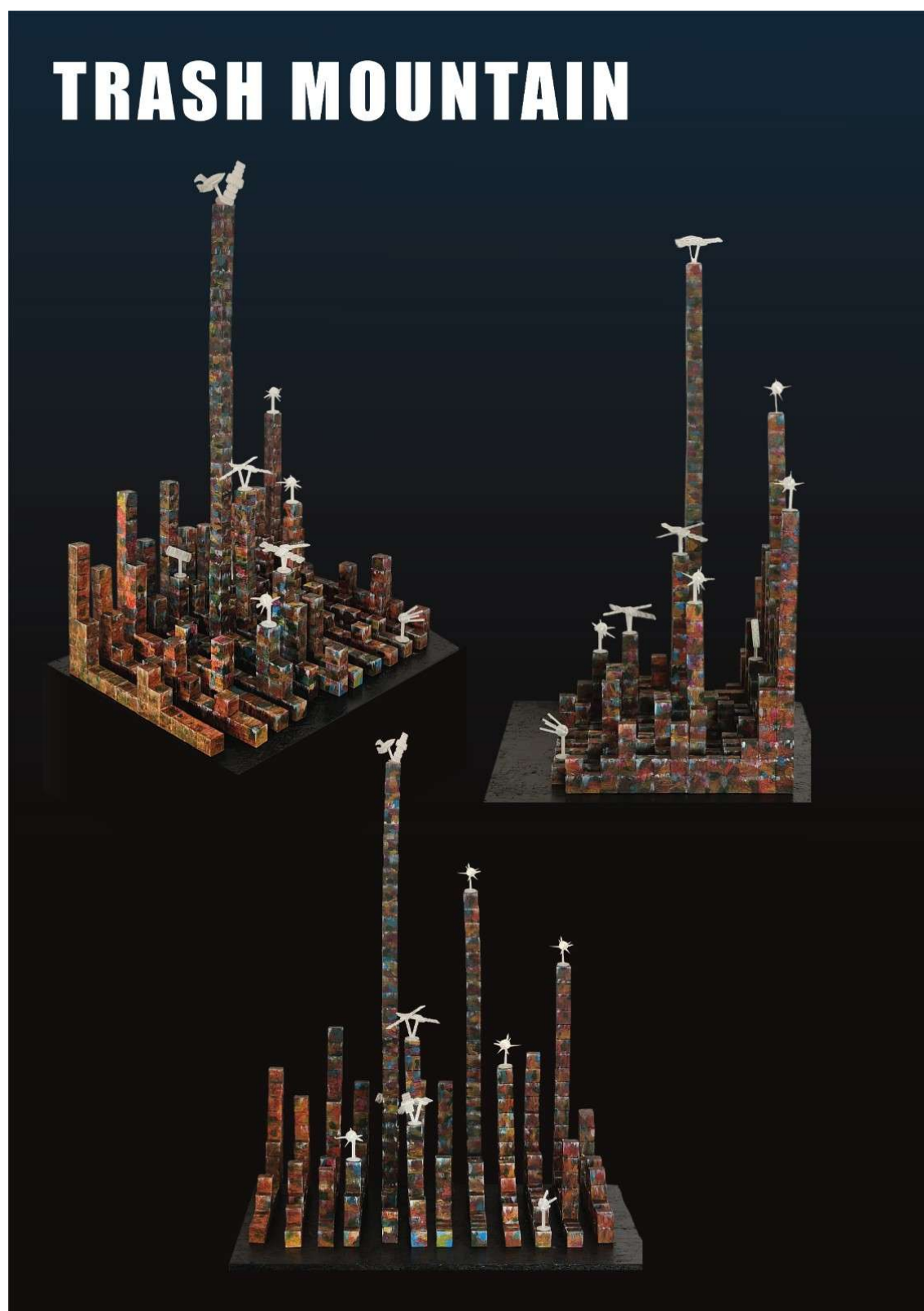


Figure A.32: Experience with different sides of the sculpture on the same image

