Process Book - Solar Explorer

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Overview and Motivation

Solar Explorer aims to present an exploratory visualization of space missions. By using data from Jonathan C. McDowell's General Catalog of Artificial Space Objects on the backdrop of the Solar System, our dashboards allow users to navigate the landscape of Solar System exploration through time. This process book documents the iterative process we took.

Our dashboard has two primary pages: the Solar System map, and the data analysis page. On the Solar System map, planets are shown in their current position, with lines drawn showing the path through the Solar System that deep space missions have taken. The page also highlights the evolution of missions through time and allows the user to interact by changing the year and selecting missions, planets, and moons.

The second page allows users to dive into the data, with scatter plots and histograms that allow users to compare various data attributes of both missions and Solar System bodies.

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Motivation

Our team has a diverse background, including expertise in astrophysics, computer science, and electrical engineering. We all share an interest in astronomy and space exploration, which prompted this topic for our project. We believe there is potential to improve how this kind of information is presented. Typically, visualizations focus on timelines and written milestones, omitting interesting information that could provide a more comprehensive understanding of the missions.

Goals

Our project has the following primary goals:

- Visually present the Solar System in an interesting way.
- Visualize the path of deep space missions in a way that helps answer questions and get a sense for overall trends using the Solar System as a backdrop.
- Allow users to explore the data by utilizing customizable and interactive visualizations.

Related Work

Existing Solar System Viewers

Our project drew inspiration from several existing solar system viewers:

- NASA Solar System Viewer This web app shows the Solar System in 3D and shows the current several NASA missions.
- Solar System Scope This viewer also maps the Solar System in 3D. It focuses on giving information related to the planets and their moons.

Space Mission-Related Work

There isn't much available for visualizing deep space missions. But these projects inspired us:

- Earth Orbit Artificial Objects Viewer This visualization focuses on visualizing artificial objects in Earth orbit, offering information on the density and distribution of satellites. However, it does not include visualizations of deep space missions or detailed information about celestial bodies. Our project will not include objects in Earth orbit.
- GCAT: General Catalog of Artificial Space Objects This is the primary data source for our project. The data is presented strictly in machine-readable tabular data files, with no visualizations or statistics. Our project will present this data in a user-friendly format.

Concepts from Class

The way we visualize mission data ended up being similar to several graph visualizations that we discussed in class, with Solar System bodies serving as nodes, and the path that missions took to navigate these bodies as edges. Also, we initially took inspiration from the "Napoleonic march to Russia" visualization for the solar system map.

Questions

Initial Questions

We started with these questions about the data:

- What is the orbit location of solar system objects, including planets, dwarf planets, moons, asteroids, and belts?
- What is the date of discovery for these objects, and what are the most recently discovered celestial bodies?
- How has the number of discovered moons around each planet changed over time?
- What are the most common targets for space missions in terms of planets, moons, or other celestial bodies?
- What is the success and failure ratio of missions sent to specific objects?
- How many shuttles, artificial satellites, and probes are currently in operation, and how has that number changed over time?
- What are the times and locations of different mission phases?
- What are some regular paths traversed by the different missions in the solar system?
- Which celestial objects are commonly used for gravity assists and orbiting?

Question Evolution and New Questions

Due to time and data constraints, some of our questions had to go unanswered:

- We decided not to look at dwarf planets (excepting Pluto), asteroids, and belts due to the sheer number of these objects, which introduces clutter and also have several missing data attributes.
- We did not consider the success and failure ratio of missions, since that information was difficult to extract from the data.
- We had to simplify the number of phases we showed for each mission, highlighting only the phases when missions visited or travelled between planets and moons.
- We also did not specifically notate gravity assists, since it's difficult to always infer when an orbit is a gravity assist or not based on the data (and it's not always clear what the dividing line is between a gravity assist and a primary mission objective - especially for missions that travel deep into the Solar System).

We also started to ask a few additional questions during the course of our project:

- What temperature are various planets?
- How do other physical attributes of planets (density, gravity) vary with respect to their other attributes or location.
- How much mass did various missions need to launch?
- How many different components (rocket parts / vehicles) were required for each mission?
- How long have various missions been ongoing?

Data

Data Sources

Our project relied on two primary data sources:

- General Catalog of Artificial Space Objects (GCAT) Data was collected from this catalog by Jonathan McDowell, an astronomer at the Harvard-Smithsonian Center for Astrophysics. The catalog contains information about all known artificial objects both in orbit around the Earth and on deep space missions, current and historical.. The data is in a CSV format and contains information about the object's name, launch date, launch site, and orbits, as well as a lot of supplementary data including details about planets and moons.

  We specifically used the following tables from GCAT:
    - `worlds` Gives information about planets, asteroids, and other worlds visited by spacecraft.
    - `satcat` Contains information about all known and officially documented artificial objects that have been to space.
    - `auxcat` Contains information about objects that have been to space but are not officially cataloged by the US government.
    - `lcat` Contains information about all known launches.
    - `ecat` Contains information about phase changes of objects while in orbit around various bodies in space.
    - deepcat Contains spacecraft events which occur in "deep space" (beyond typical Earth orbits).
    - `lprcat` Contains spacecraft events which occur near the moon or other planetary bodies.
    - `hcocat` Contains spacecraft events for spacecraft in orbit around the Sun.
- NASA Jet Propulsion Laboratory (JPL) Horizons Data System To supplement the GCAT data and obtain more detailed information about planetary bodies, we utilized NASA JPL's Horizons data system, accessed through their public REST API and tables of information about Planetary Satellites.
- Le Systeme Solaire public API to supplement bodies data with additional variables such as average temperature, discovery date, gravity, density, among others.

Data Cleaning and Preprocessing

The data is downloaded using a python file `process_data.py` that also performs data cleaning.

The GCAT data uses several unique standards for dates, numerical values, and IDs, so the majority of the data cleaning involved reading in the values and parsing the format according to

McDowell's specifications. The data was then saved in a JSON format for easier access from JavaScript.

Specifically, the data cleaning involved:

- Parsing McDowell's "vague date" format into an ISO-8601 formatted date and a precision value.
- Mapping the relationship between objects and their parent objects (space missions often involve rockets with multiple components, discarded components, counterweights, etc. in addition to the primary payload).
- Deciding which object involved in a mission is the "primary" payload (missions can have human payloads, pressurized payloads, general payloads, and rocket components).
- Mission data details are encoded in different languages because it is launched by different nations. Translating it into English is not advisable as it may introduce complications in processing.

Calculating Planetary Positions

The JPL Horizons Database gives positions and orbital elements at a single point in time. In order to get the interactivity that we wanted, we needed to download orbital elements at a grid of times, and then interpolate between those points to calculate the orbital elements at any time. With these orbital elements, we could calculate the position of the planets.

Our original attempt at writing code to calculate the current position of the planets was not successful. After revisiting the code, we noticed the following issues, which each compounded to give drastically incorrect results:

- The code was inconsistent in its use of time units (years vs. days), which made converting from one to the other ambiguous.
- Some orbital elements wrap from 360 to 0 degrees (or vice versa), which was not accounted for in the linear fits we were using to interpolate.
- Some of the logic was incorrect, such as the calculation of the mean anomaly.
- The JPL ephemeris data for Earth has some strange computational artifacts due to the coordinate system being based on the Earth's autumnal equinox. Our code did not account for this.

After fixing these issues, our code now correctly calculates the positions of the planets at any given time. The code is written in Python and is available in the `calculate_planetary_positions.py` file.

Exploratory Data Analysis

Initial Exploration

Because we were already familiar with the sort of data we expected for the Solar System, we started visualizing that data using what we expect to be similar to the final visualization format, utilizing a logarithmic scale.
As we started looking at the data related to missions in a tabular format, we realized that there were many missions between some Solar System bodies, including Earth → Moon, Earth → Sun, and Earth → Earth. We would need some way to clearly distinguish each mission in a limited amount of space. Having the planets in a line like this would not be effective, and placing them in fixed arbitrary positions would render the position channel unused. That is why we came up with the idea of placing the planets in their accurate positions at the selected date.
We also used python histograms and scatterplots to visualize the data and to decide wich variables were significant enough to plot in the data explorer dashboard.

Design Implications

We made these decisions to help make a large number of missions feasible to visualize:

- **Realistic Locations:** Planets should be plotted in their proper location, to help reduce the overlap between mission paths and to use the position encoding channel.
- **Mission Path Encoding:** Mission paths would be drawn with bezier curves that expand outward to allow all the missions between two bodies to be displayed at the same time. An alternative option accumulating the paths into single width encoded links was considered, but it would mean loosing individual mission path data or requiring additional interactions, grouping edges and performing semantic zoom. Finally, we decided that the individual bezier corvus evenly spaced would provide a sufficient notion of the number of missions visiting each solar system body.
- **Interactivity:** Users should be able to zoom, select objects, and change the year.

Design Evolution

Design Goals and Considerations

In designing our visualization, we considered the following key tasks:

Space Missions Map

- Tasks:
    - **Discover:**
        - Outliers (missions to distant and/or unexplored objects)
        - Trends (most explored objects and most navigated paths)
    - **Search:**
        - Explore (location unknown, target unknown) the solar system map with all its objects and missions.
        - Locate (target known, location unknown) and find the positions of different objects in the solar system at a given point in time.
    - **Enjoy (hopefully):** Create a visually appealing and engaging experience that encourages exploration.
- Interactions:
    - **Animated Transitions:** Smooth transitions across time to visualize the changing positions of solar system objects and missions.
    - **Selection/Highlighting:** Allow users to hover over celestial objects or missions to view additional information in tooltips.
    - **Navigation:**
        - Translation and geometric zooming are used to explore the map.
        - Semantic zooming is used to explore the location of mission pieces (finally not implemented due to the vast number of pieces and time constraints).
- Encodings:
    - **Orbits:** 1D lines, using vertical and horizontal position channels.
    - **Objects:** 0D points, using vertical and horizontal position channels, and hue/texture channel for encoding the object type.
    - **Missions:** 1D lines, using vertical and horizontal position channels.

Data Explorer

Dashboard 2 (Data Explorer) provides a dedicated space for users to dive into the quantitative aspects of celestial bodies and missions. It will include:

- **Scatterplots:** Users can visualize relationships between different variables (e.g., distance, radius, launch date) through interactive scatterplots.
- **Histograms:** Histograms allow users to analyze the distribution of specific variables, gaining insights into patterns and trends.

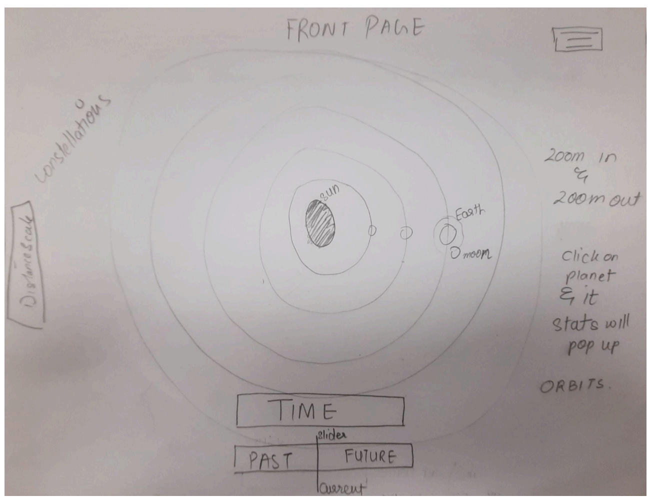
- **Variable Selection Dropdowns:** Users can dynamically choose which variables to display on the scatterplots and histograms, tailoring the exploration to their interests.

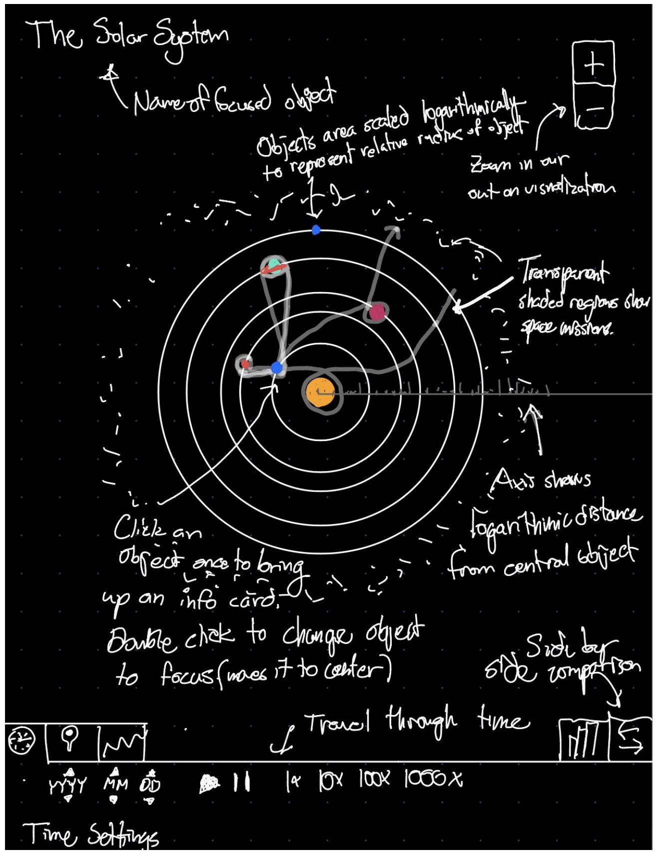
Initial Exploration

We explored various visualization options, including:
- A 2D or 3D model of the solar system
- A network diagram of mission connections
- A timeline-based representation of mission events

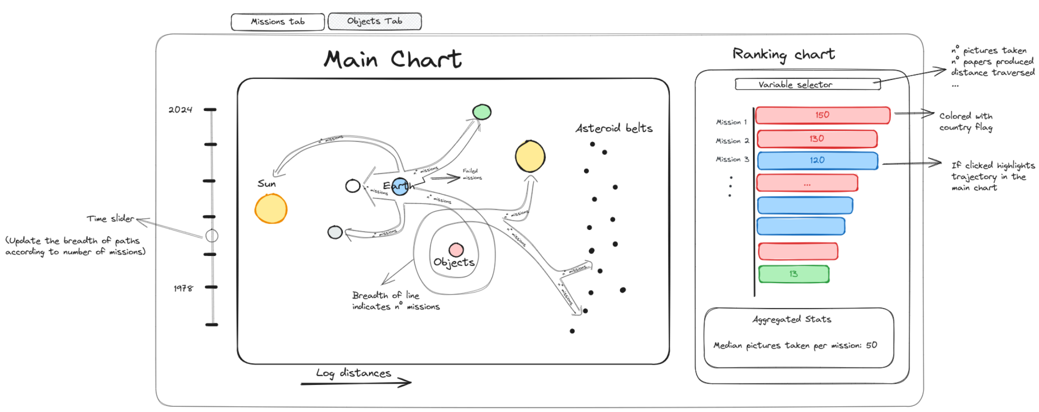
Chosen Approach

After splitting up to come up with individual designs, we all seemed to come up with a similar design for the home screen, utilizing a model of the Solar System. Here are the sketches we all proposed:

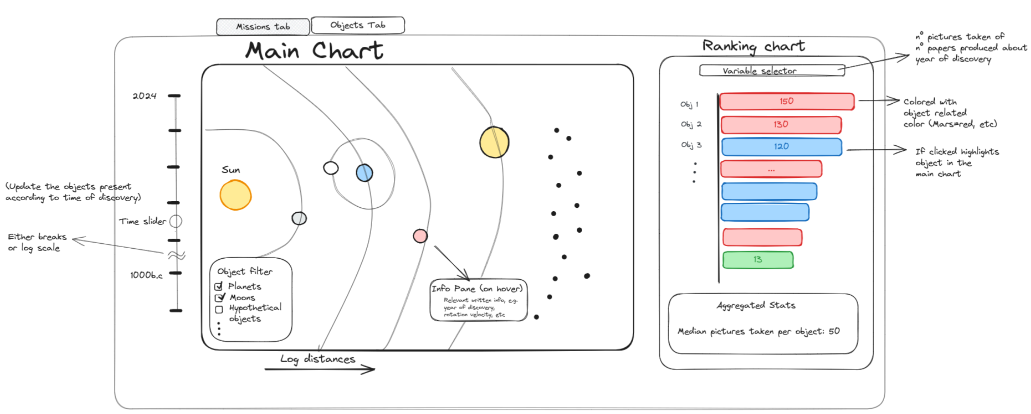




The Solar System
Name of focused object
Objects area scaled logarithmically to represent relative radius of object
Zoom in our out on visualization
Transparent shaded regions show space missions.
Axis shows logarithmic distance from central object
Click an object once to bring up an info card.
Double click to change object to focus (moves it to center)
Side by side comparison
Travel through time
YYYY MM DD
1x 10x 100x 1000x
Time Settings

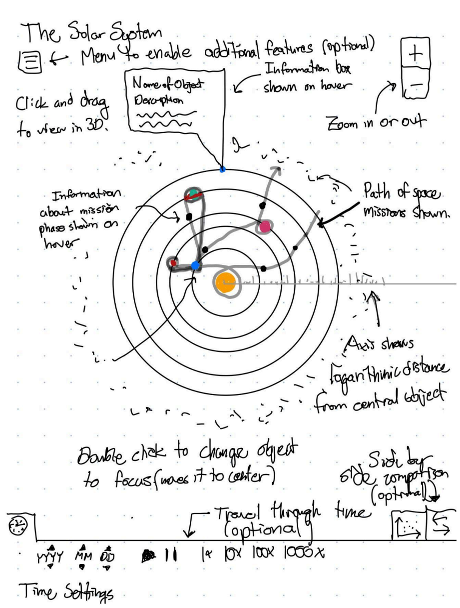


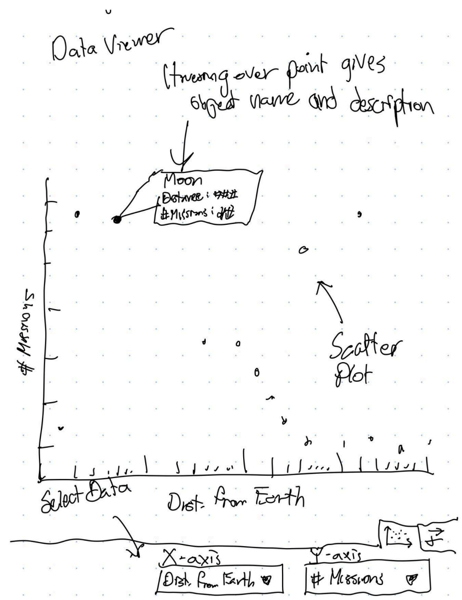
Missions tab
Objects Tab
Main Chart
2024
1978
Time slider
(Update the breadth of paths according to number of missions)
Sun
Earth
Failed missions
Objects
Breadth of line indicates n° missions
Asteroid belts
Log distances
Ranking chart
Variable selector
n° pictures taken
n° papers produced
distance traversed
...
Mission 1
Mission 2
Mission 3
150
130
120
...
13
Colored with country flag
If clicked highlights trajectory in the main chart
Aggregated Stats
Median pictures taken per mission: 50



Missions tab
Objects Tab
Main Chart
2024
1000b.c
(Update the objects present according to time of discovery)
Time slider
Either breaks or log scale
Sun
Object filter
Planets
Moons
Hypothetical objects
Info Pane (on hover)
Relevant written info, e.g. year of discovery, rotation velocity, etc
Log distances
Ranking chart
Variable selector
n° pictures taken of
n° papers produced about
year of discovery
Obj 1
Obj 2
Obj 3
150
130
120
...
13
Colored with object related color (Mars=red, etc)
If clicked highlights object in the main chart
Aggregated Stats
Median pictures taken per object: 50

We settled on a 2D interactive map for its clarity and ease of navigation. This design utilizes sizes and distances to represent the planetary scales. It also includes a second page with a quantitative approach to visualizing the data. Here is our final proposed design:





Dashboard Structure

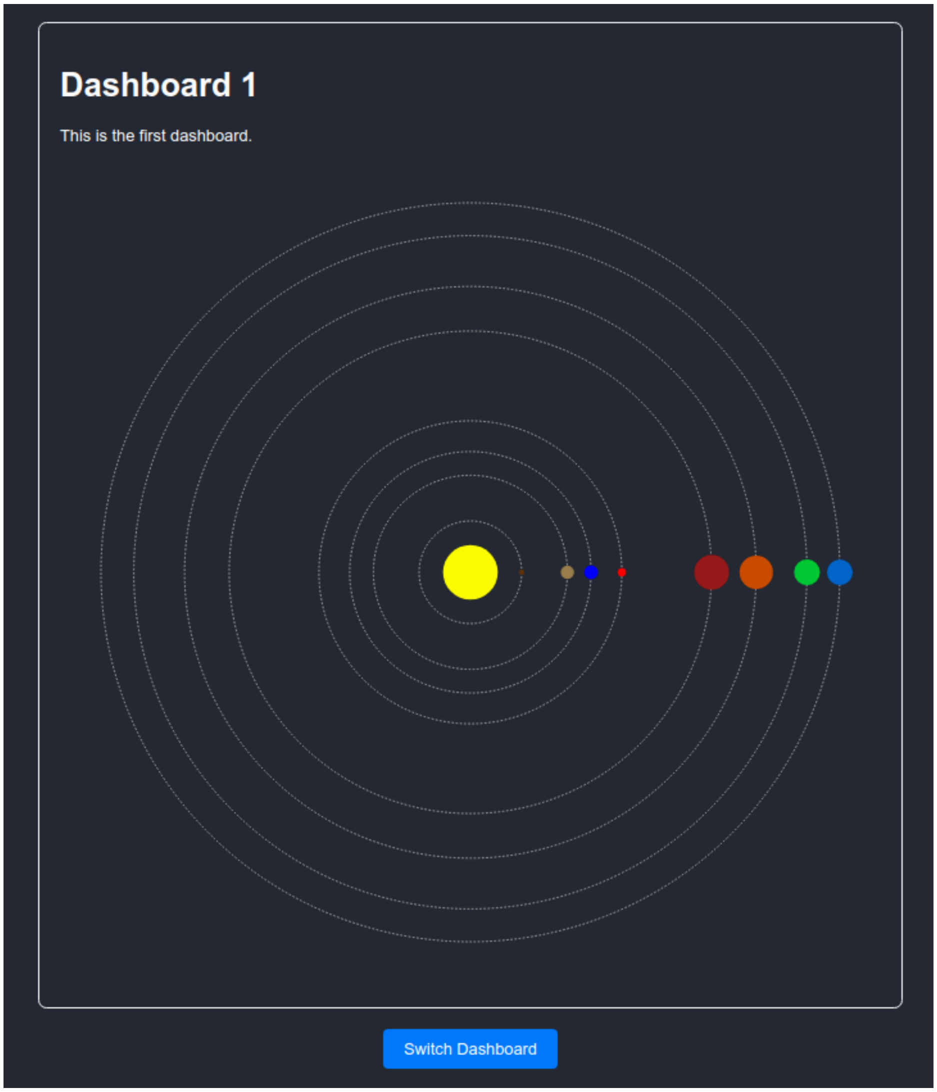
While our initial proposal focused on a single, comprehensive view, we later incorporated scatterplot and histogram visualizations to provide a focused exploration of planetary properties. This led to a two-dashboard structure:

- **Dashboard 1:** The main solar system visualization with interactive elements.
- **Dashboard 2:** A Data Explorer with scatterplots and histograms for deeper analysis.

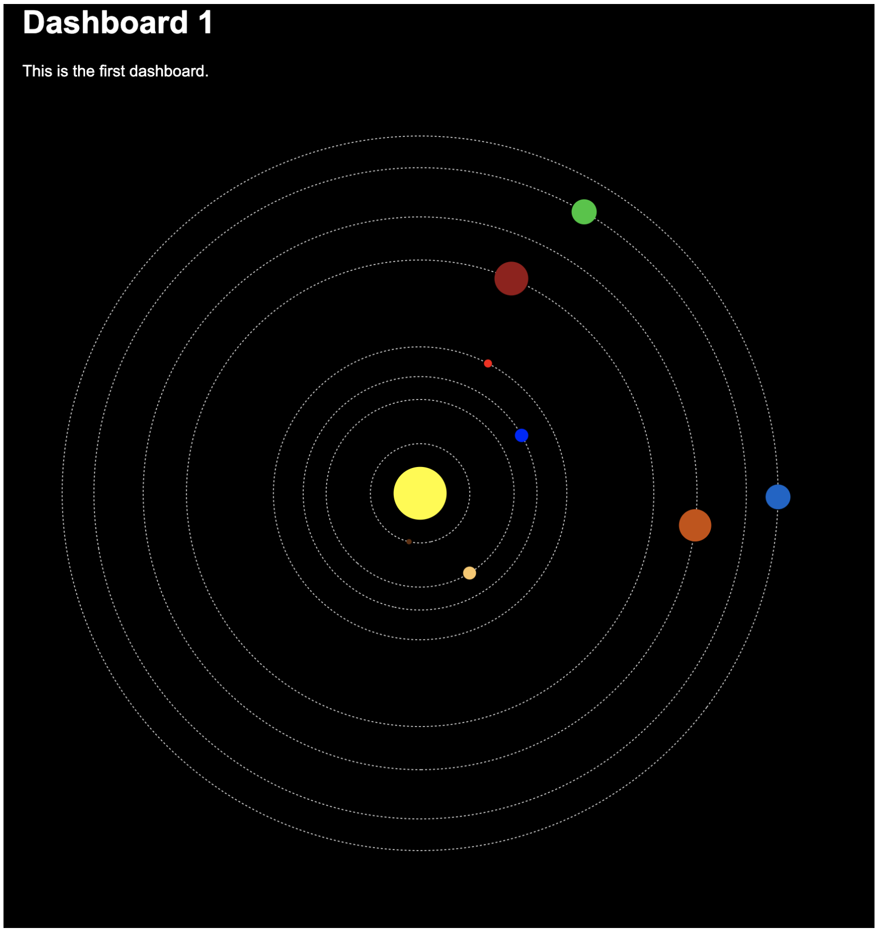
Prototype Iteration

Solar System Map

- **First Prototype:** A basic solar system visualization with planets represented as colored circles on a dark background, and a Log scale used to determine the planet's distance from the Sun. Although not visible in this image, the Planet's name appears when hovering over the planet.



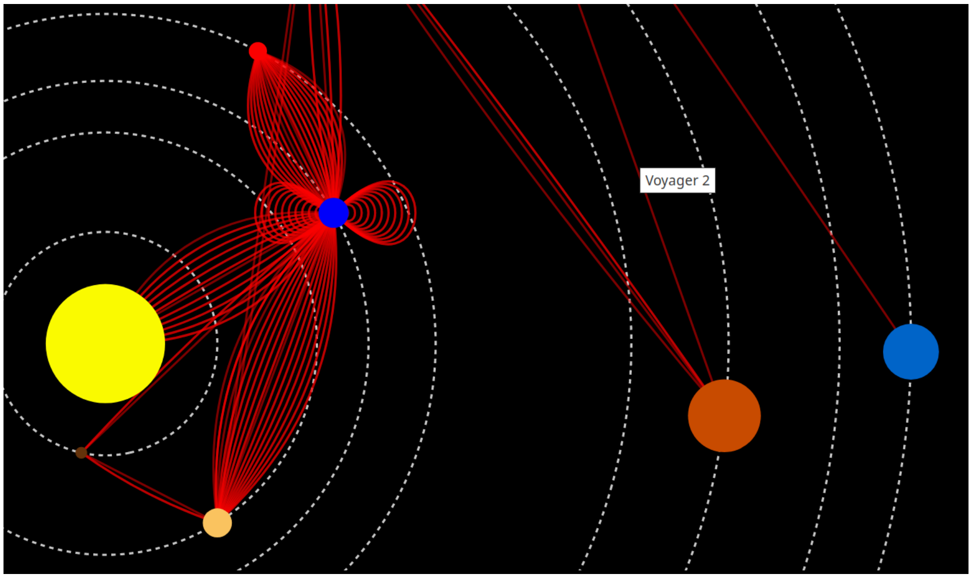
- **Planetary Positions:** The prototype was then updated to display the planets in their current relative position, as discussed above.



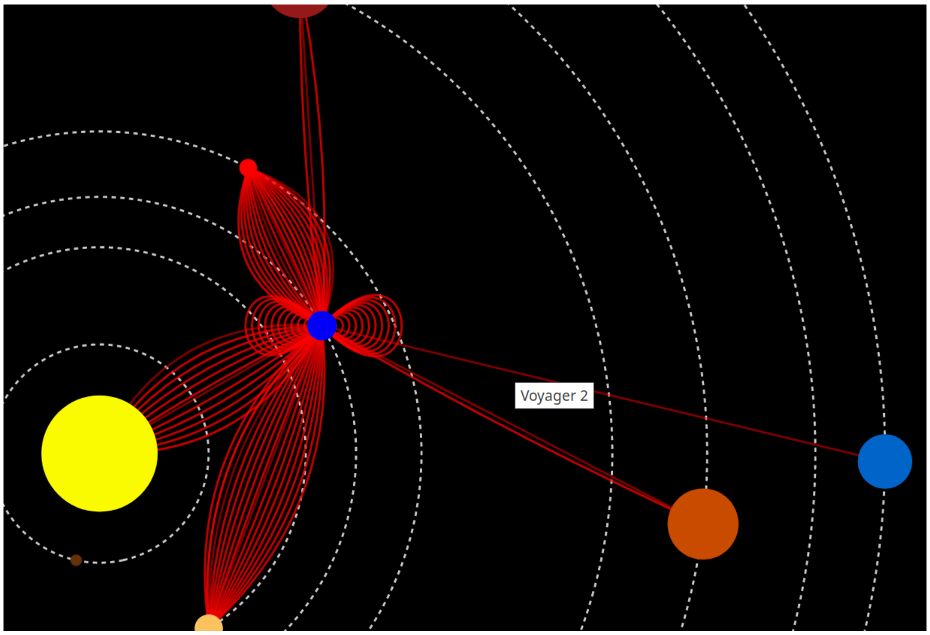
- **Mission Paths:** We then had the task of visualizing the mission paths using Bézier curves with control points. We had to decide between two options:

  (1) Displaying the path an object took, including several curves between every planet that the mission visited.
  (2) Displaying one curve showing the path between the mission origin (usually Earth) and its final destination.

(1)



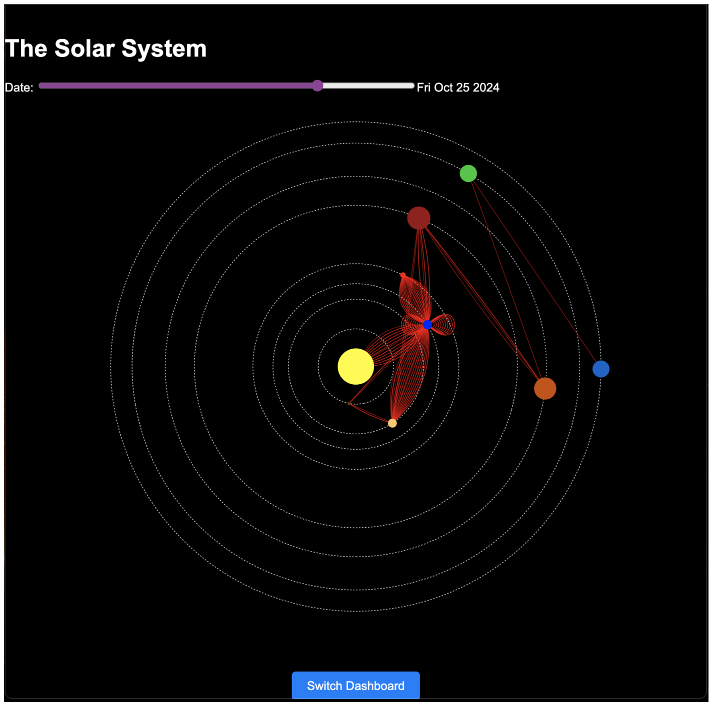
(2)



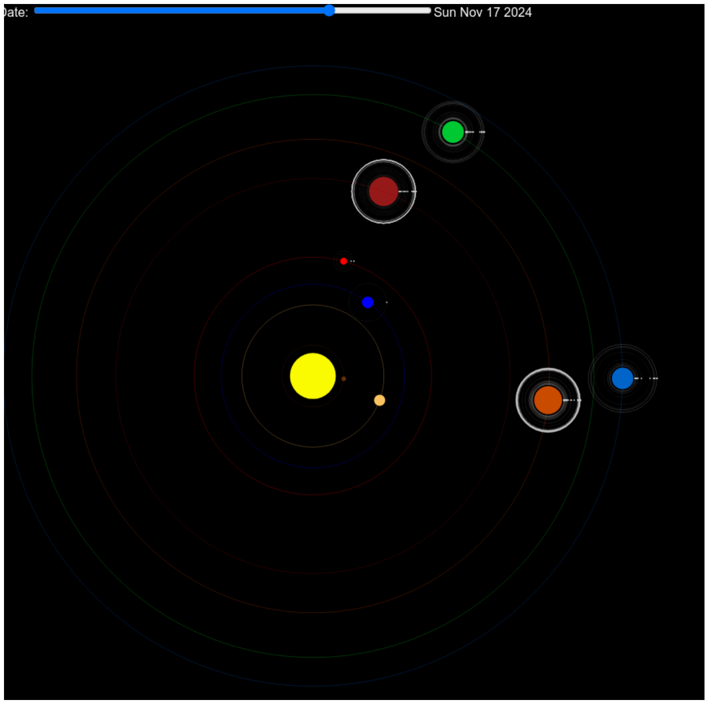
In the end, we opted for the first option, even though it is slightly more cluttered, because missions like Voyager 2 visited several planets in its mission through the Solar System, and that data would be lost using the second approach.

We tried using d3's force simulation and cytoscape to calculate the curves, but it interfered with other elements of the plot in a way that was difficult to control, so we just calculated the curves manually.

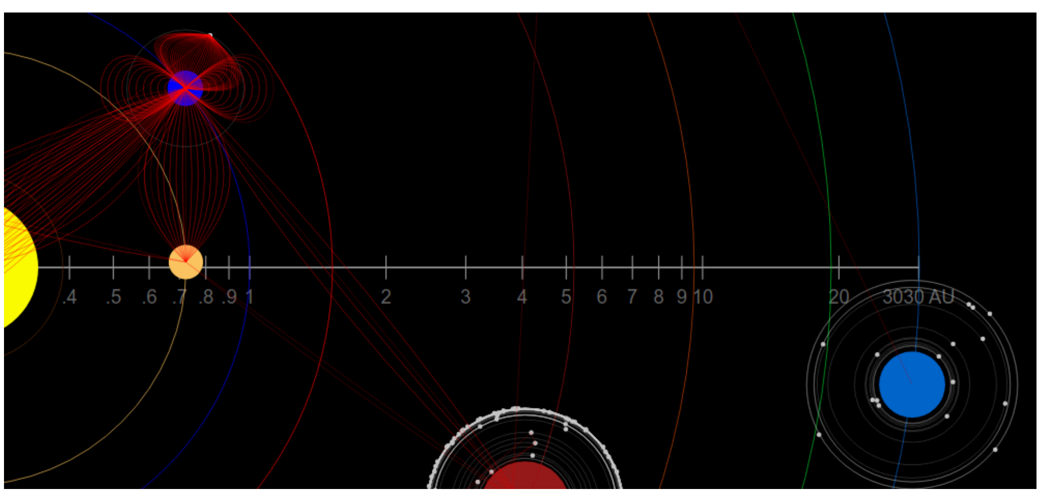
- **Time Slider:** We then decided to introduce a time slider (as discussed above) to allow users to dynamically change the date and observe the corresponding changes in planetary positions.



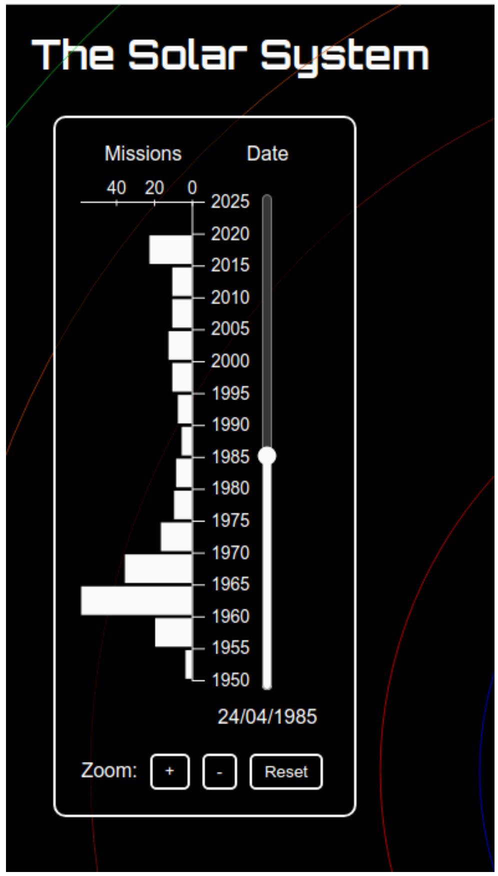
- **Satellites:** Satellites were added to the visualization, represented as small circles orbiting planets. Some challenges faced with the satellite representation were as follows:
    - **Visual clutter**: The high number of satellites made them impossible to distinguish for some planets. Our initial idea was to calculate accurate positions for the satellites, as we did with the planets, but this would yield a visually unordered arrangement and make them difficult to identify. Instead, we arranged them all at the 0º orbit angle. Additionally, we lacked data on the radius of each satellite, which made them appear uniform. To address these problems, we added color coding for the most important satellites to make them easily distinguishable and enriched the original data with satellite radius information. We also introduced several zoom levels to allow users to find very small satellites such as Phobos and Deimos.
    - **Scale differences**: The vast difference in distances between a planet and its satellites and between the Sun and the planets made it impossible to use the same scale. We experimented with different scaling options for satellite radii and planet-to-satellite distances. Ultimately, we decided that the easiest-to-explore option was to use an accurate logarithmic scale for planet-to-satellite radius and distance. This means that the sizes and distances between satellites of different planets are no longer directly comparable, but it was a trade-off we made to make the satellites easier to find.



- **Styling and Distance Scale:** Styles for orbits, planets, and controls were refined, and a distance scale was added to the map. We color-coded the planets and their orbits to make them easily identifiable, using a logical color selection aligned with commonly associated planetary colors, while taking some licences (orange Saturn, green Uranus, etc) to enhance distinguishability. We also considered using textures or real planetary images as backgrounds for the circles. However, this idea was discarded because it made distinguishing the planets more difficult and, contrary to our initial expectations, worsened the overall appeal. This was due to two main issues: the clash between the realistic style of the planet images and the minimalist design of other components, and the incorrect positioning of the sunlight shading on the images, which made the planets seem out of place with the rest of the visualization.

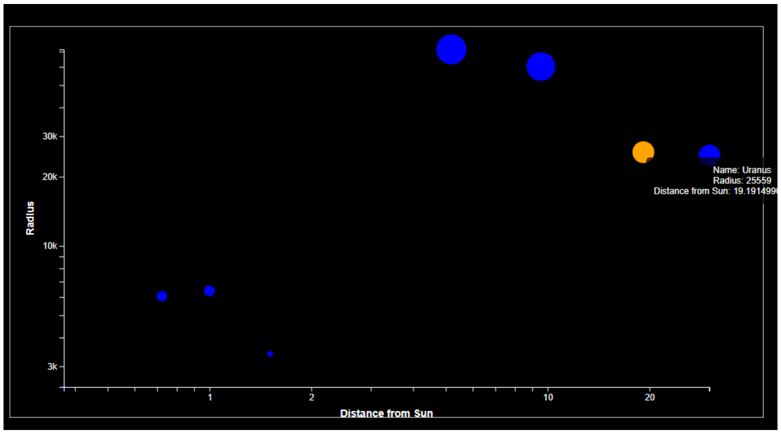


- **Time Slider Histogram:** The time slider was enhanced with a mission count histogram visualization and zoom controls. The decision to include the mission histogram visualization was made to give users a clearer understanding of the history of missions, making it easier for them to explore through time in a more informed manner.

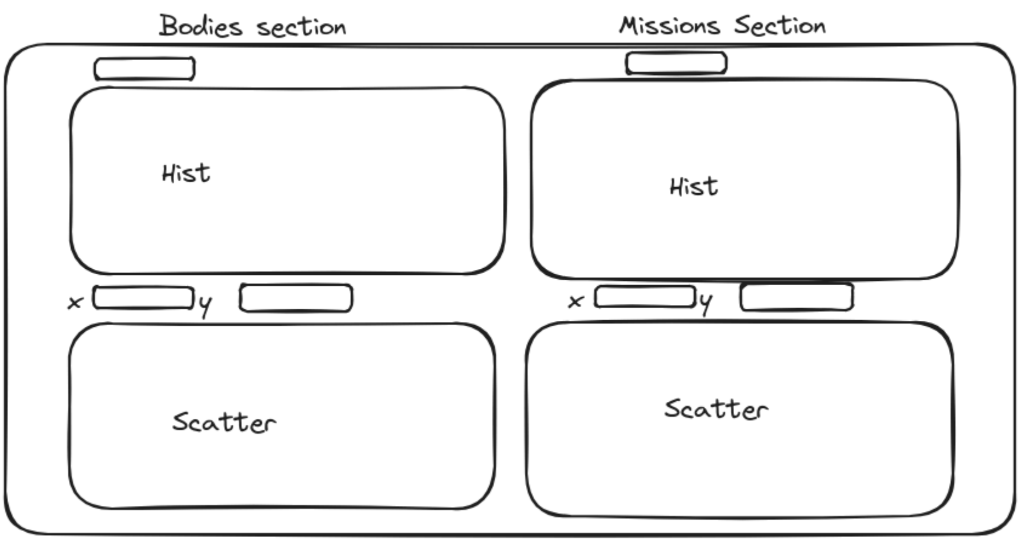


Data Explorer

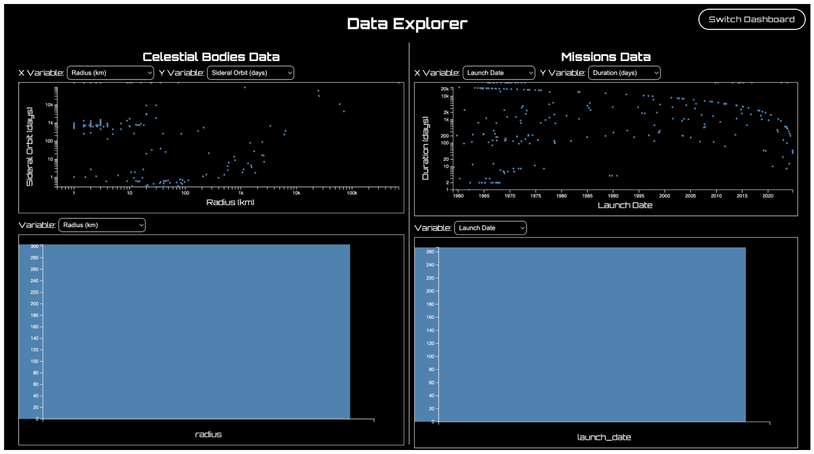
- **Initial Prototype:** Our initial prototype plotted only two data attributes and included a tooltip on hover. However, it provided limited value due to the narrow dataset it represented (e.g., distance from the Sun). To address this, we decided to expand the variables in the visualization:



- **Improved Dashboard 2 Design:** The updated design organizes the interface into two main sections: Bodies Section and Missions Section. Each section features two types of visualizations: a histogram (labeled "Hist") and a scatter plot (labeled "Scatter"). We took inspiration from a homework assignment, adapting the concept of a four-plot display instead of the single plot with a dataset and plot selector. This design simplifies drawing insights across datasets by reducing user actions (fewer selectors to click) and allowing simultaneous visibility of current mission and planet selections.



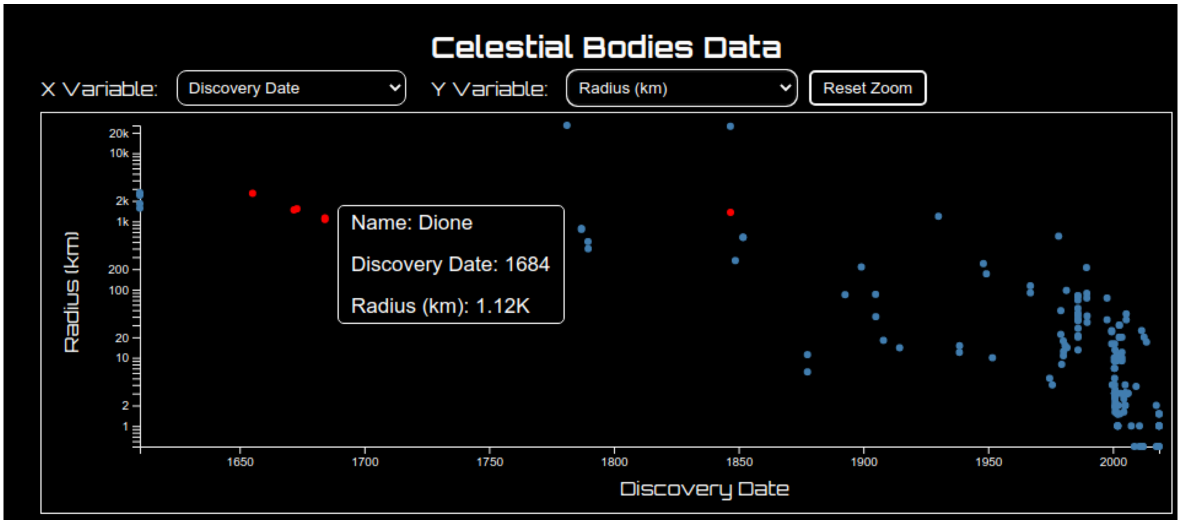
- **Additional Plots and Interactivity:** Additional plots were included on the page, highlighting both celestial bodies and missions in the quantitative data. Shown on the bottom are supposed to be histograms, though they were not functional at this stage.

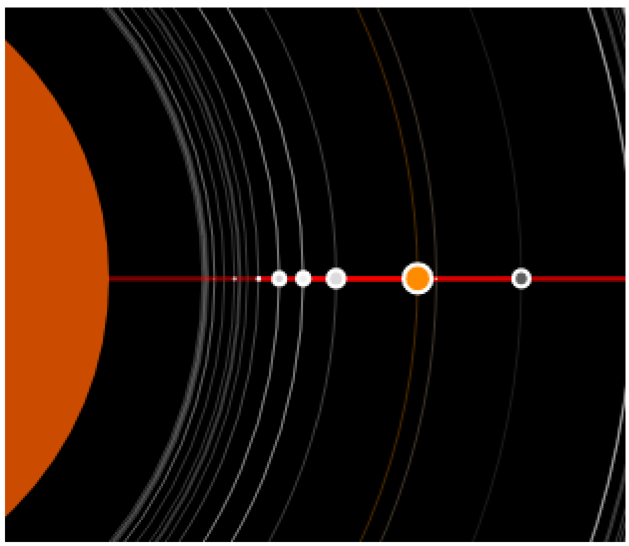


- **Data Explorer Improvements:** Histograms were fixed. Data transformations, filtering, and scale adjustments were implemented based on selected variables. This was necessary because different variables require different scales, and some individual data points with missing values or extreme outliers caused distortions. Additionally, individual zoom functionality was added to each plot. One important challenge in representing distributions for variables with a wide range of values was designing interpretable histograms. We used log scales, creating variable-width bars to show the distribution. This raises concerns about interpretability (for example, “is the are of the height or the area of the bar encoded with the count?”), which we aim to mitigate through the use of expressive tooltips that explain the variable ranges and the bin count.

- **Selection Interactions:** Selection interactions were implemented to link the solar system map and the data explorer, highlighting selected objects in both views.

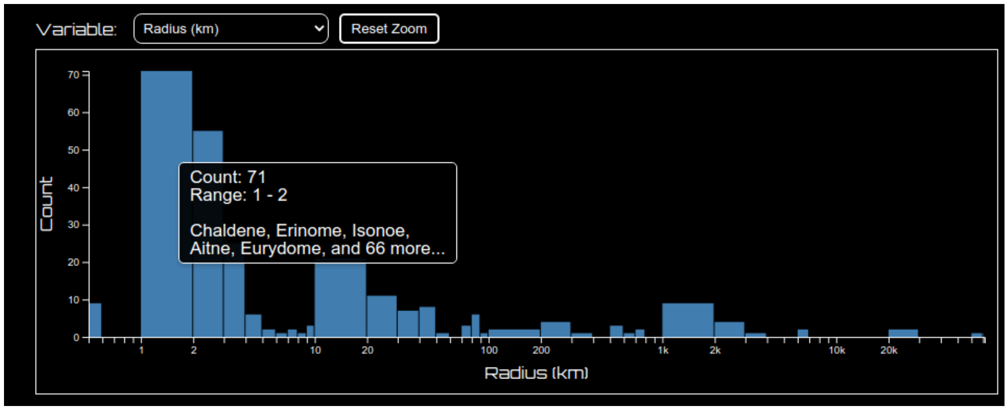
In the following images we see the selection interactions that were added. Moons in the Solar System map are marked with a white circle, and the same moons are marked with a red scatter plot point on the data Explorer dashboard.





Common Elements

- **Tooltips:** Tooltips were designed to be both informative and easy to read. Depending on the visualization, they display relevant details such as object names, key attributes (e.g., radius, discovery date, gravity, temperature), mission data (e.g., launch date, destination, path, duration, and mission pieces), and contextual information like variable values for scatterplots or bin details for histograms, including object counts, ranges, and examples. To enhance readability, a clear, simple font was used instead of the decorative one (Orbitron), and high-contrast black-and-white colors were chosen for the text and background.



- **Color Usage:** A high-contrast theme is applied on all the the charts. The idea behind this was to use a neutral background and sparingly incorporating color for a simple, easy to understand visualization with an effective use of the pop-out effect for the selected elements (red).

- **Other Gestalt Principles**: Here, we detail some of the Gestalt principles applied, which we emphasized further following the peer feedback activity:
    - **Similarity:** Consistent use of colors, fonts, and graph styles across the dashboards creates a cohesive design. Uniform shapes (e.g., scatterplots and bar charts) and symmetries help indicate similar data types or functionalities.
    - **Figure-Ground:** A black background with brightly colored data points and text ensures that the data visualizations stand out clearly as the figure, while the background remains unobtrusive as the ground.
    - **Connection:** Mission trajectories serve as explicit visual connections.

- **Chart junk:** Initially, we considered adding a background image featuring stars visible from the Solar System to enhance the visual appeal. However, this idea was discarded because it conflicted with the use of the pop-out effect in the Solar System map, making small satellites harder to locate and interfering with the scatterplot.

Variations from Proposal

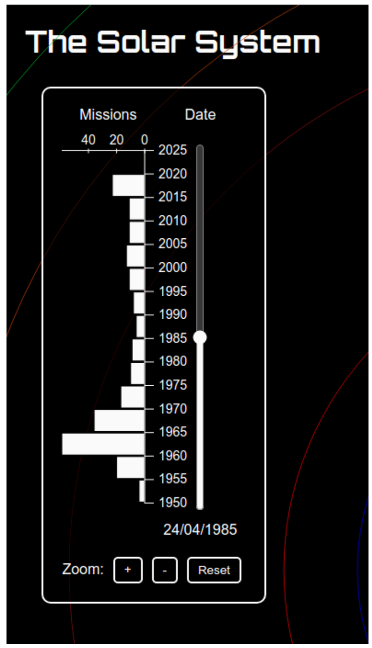
Compared to our proposed design, our final design is similar in the data tasks it allows the user to complete, but visually, we made quite a few changes, described in the sections above. This was partly due to time and data constraints, which shifted some of the questions we were answering (as described above). However, our design shifted primarily as we became more familiar with d3 and the good design principles we discussed in class.

Implementation

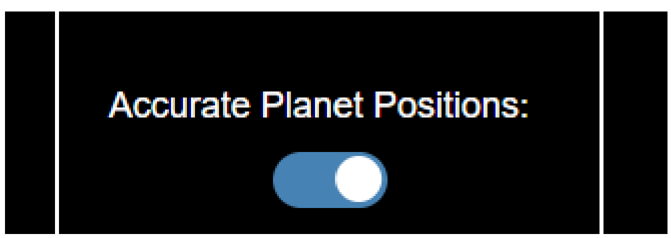
Interactive Elements

Our visualization features several interactive components:

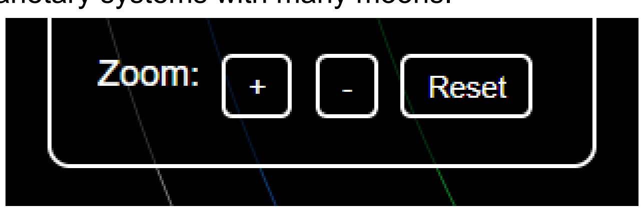
- **Time Slider:** A vertical slider enables users to filter missions by launch date, dynamically visualizing the evolution of space exploration.



- **Accurate Planet Positions Toggle:** A toggle switch allows users to control whether planet positions are updated to the proper position when the date slider is moved. Turning this off can allow users to more easily see the change in the number of missions as time progresses, while turning it on allows users to see the change in the position of the planets through time.



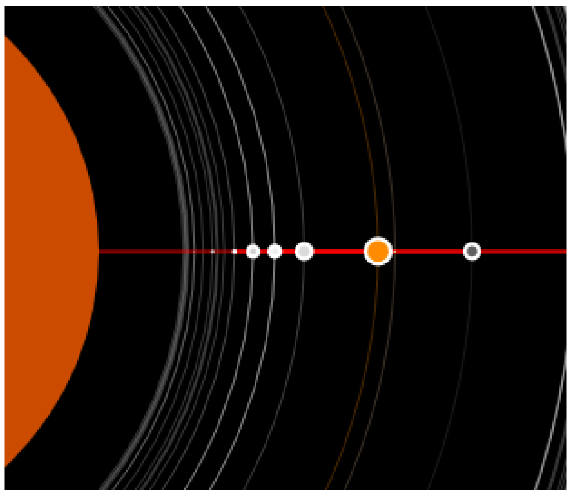
- **Zoom Controls:** Buttons for zooming in, zooming out, and resetting the zoom provide users with control over the visualization's scale, facilitating the exploration of both the full solar system and planetary systems with many moons.

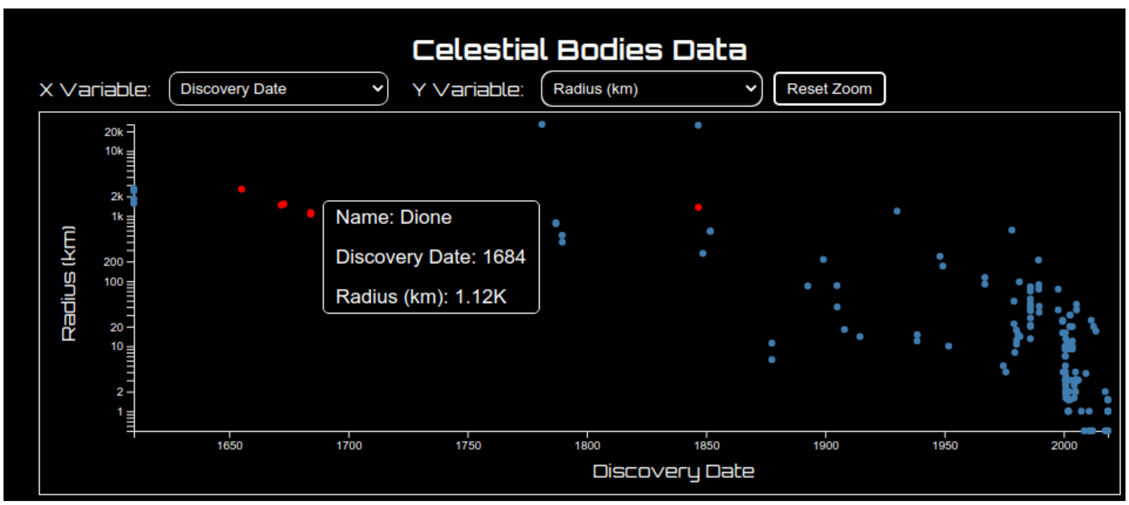


- **Switch Dashboard:** A prominent button enables users to switch between Dashboard 1 (solar system visualization) and Dashboard 2 (Data Explorer).

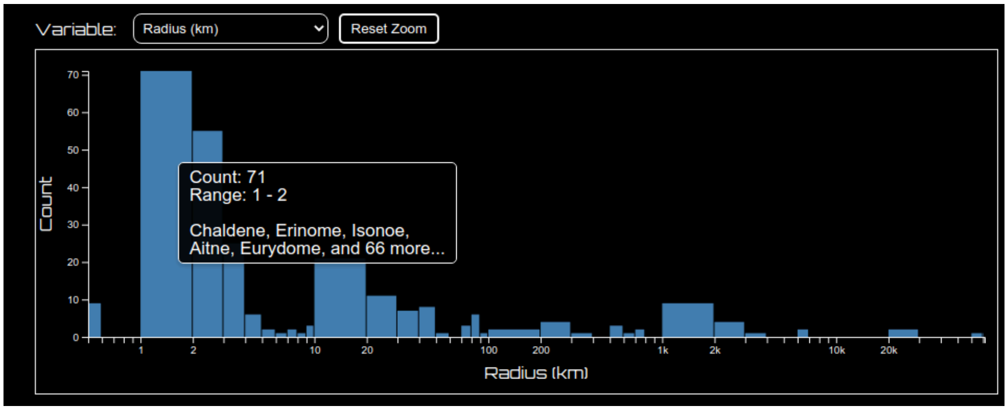
- **Selection Interactions:** Selection allows users to see the link between objects on the map and objects on the data explorer. A "Clear Selection" button appears to easily clear all selected items.

Selected items are highlighted in both the map and the data exploration page. This selection management system facilitates coordinated interactions and enhances the user's ability to explore connections between different aspects of the data.





- **Tooltips:** Tooltips show up when hovering over any items in our visualizations



- **Zooming and Panning:** Users can zoom in and out of the solar system and pan across the visualization to explore different regions.

Evaluation

Insights Gained from the Data

Working with the data and implementing our visualization helped us find several interesting insights:

- The order in which different Solar System objects were discovered contradicted some of our previous beliefs. For example, large planets like Neptune and Uranus were discovered much later than some of Jupiter's moons. However, a certain pattern does exist between an object's size, its distance from the Sun (given by the orbit's semi-major axis), and its discovery date. Also, we can easily distinguish some moments in time that a specific scientific project discovered several small objects at once.
- Logical patterns are visible among variables such as temperature, semi-major axis, sidereal orbit, and density.
- The relationship between the number of components in a mission, the vehicle's weight, and the mission duration turned out to be less linear or straightforward than we initially believed. In other words, the complexity of a spacecraft does not necessarily imply greater mass, nor does it determine how long the mission will last.
- We can clearly see a trend towards increasing spacecraft weight in recent years, alongside a resurgence of more active space exploration.
- The most explored Solar System objects (excluding Earth) are, as expected, the Moon, Mars, and Venus, with minimal exploration of the outer planets (single digits number of missions that visited many objects on their path).
- The most common routes to the inner Solar System involve direct travel using a heliocentric orbit, although paths utilizing Venus and Mercury are also present. For missions to the outer Solar System, direct paths are nonexistent: Jupiter gravity assists appear to be essential.

Answering Our Questions

What is the orbit location of solar system objects, including planets, dwarf planets, moons, asteroids, and belts?
We were able to answer this question using the Solar System map visualization. As noted previously, we opted not to show dwarf planets (other than Pluto), asteroids and belts, and we don’t yet show the accurate location of moons. Users can visualize the location of the planets at any time in space travel history using the time slider that we’ve included in the visualization.

What is the date of discovery for these objects, and what are the most recently discovered celestial bodies?
On the Solar System map, users can hover their mouse over a planet or moon to see its discovery date (except for planets which are visible to the naked eye, which have been observed throughout human history). Using the Data Explorer dashboard, users can plot the

exploration date against several other data attributes to see how attributes like the object's radius affect its discovery date.

How has the number of discovered moons around each planet changed over time?
This is one question that isn't directly answered, but can be discovered by using the selection feature. By navigating in the Solar System map to a specific planet, a user can select each of the moons of that planet, and then switch over to the Data Exploration dashboard to see the discovery date plotted on a scatter plot, with the selected moons highlighted in a different color.

What are the most common targets for space missions in terms of planets, moons, or other celestial bodies?
This question is easy to visually see on the Solar System map. Objects which have had many visiting missions will have many lines representing these missions extending out of the object. Because of the way the mission curves expand so that all the missions are visible, the objects with more visiting missions will have a set of mission curves that appears wider and denser. Additionally, on the Data Explorer dashboard, users can select "Mission Destination Count" on the Celestial Bodies Data to see how many missions have visited each body.

What is the success and failure ratio of missions sent to specific objects?
As discussed previously, we were not able to answer this question with the datasets we obtained.

How many shuttles, artificial satellites, and probes are currently in operation, and how has that number changed over time?
This question isn't directly answerable with our data, but one proxy for this could be the number of launched missions. On the Solar System map dashboard, the histogram showing the number of launches binned by year can give a sense for how many missions were operating at a given time. On the Data Explorer dashboard, users can plot "Mission Duration" and "Launch Date" to also get a sense of which missions are still operating.

What are the times and locations of different mission phases?
Although we simplified the mission phases that are shown (as discussed previously), our Solar System map dashboard still allows users to see each mission divided up into phases representing the travel between different destinations. Long-running missions like Voyager 2 have several legs of the mission, with stops at multiple planets. These locations can be easily seen on the map. The times aren't directly represented in our visualizations, which is a potential area for improvement.

What are some regular paths traversed by the different missions in the solar system?
Similar to the question about the most common targets of space missions, the Solar System map allows users to easily track common routes through the Solar System. For example, as discussed in the previous section, missions to the outer Solar System seem to always visit Jupiter along the way.

Which celestial objects are commonly used for gravity assists and orbiting?
Our data doesn't contain information about which missions are visiting planets only for the purpose of a gravity assist, so this question isn't able to be directly answered using our visualization. Users with additional physics knowledge, though, may be able to determine which missions must have needed a gravity assist based on the data that's present.

Visualization Effectiveness

Overall, we think our visualization effectively communicates key information about space missions and encourages interactive exploration, fulfilling our goal of making this space mission data more accessible. The combination of the solar system map and the Data Explorer, linked by interactivity, provides both a broad overview and the ability to look into specific details. Users can explore whatever data they are most interested in.
Some elements of our visualization aren't ideal. For example, visualizing the sheer number of moons around planets like Jupiter and Saturn proved to be difficult, especially given their small size relative to the planet they are orbiting. We also could have done a better job of dealing with overlapping mission trajectories, since these are difficult to navigate.

Potential Improvements

- **3D Visualization:** Incorporating a 3D visualization could provide more immersion.
- **Real-time Data:** Since we live in a new space age, integrating real-time mission data would add a dynamic element to the visualization and allow users to track ongoing missions.
- **Storytelling:** We could enhance the storytelling aspect by incorporating more detailed narratives about specific missions, including images and key events, particularly focusing on mission failures and crash landings as mentioned in the proposal.
- **Moons:** Finding a better way to visualize a large number of moons (perhaps by adding filtering or additional visualizations would help make the design more effective.