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IIT Bombay

P2 Report

Project Title:

Visually Representing Deep Time:
An Attempt at Understanding the Cause-and-Effect Relationships leading to Evolution of Life on Earth

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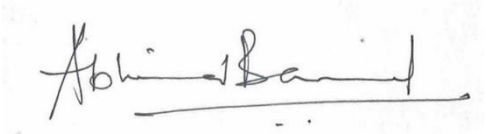
Declaration

I declare that this written document represents my ideas and interpretation of the data derived from literature, in my own words. I have tried (to the best of my capabilities) to adequately cite and reference the original sources wherever others' ideas or words have been included. I also declare that the work is not plagiarized by any means and was the outcome of exploration with my mentor. I have not misrepresented or falsified any information in my submission, all such data has been referred from reliable sources. I understand any violation of the above can lead to disciplinary action by the Institute and evoke penal action.



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November 2022

Approval Sheet

The Interaction Design Project II titled “Visually Representing Deep Time: An Attempt at Understanding the Cause-and-Effect Relationships leading to Evolution of Life on Earth” by Abhinav Bansal, Roll Number 216330003 is approved in partial fulfilment of the Master in Design Degree in Interaction Design at the IDC School of Design, Indian Institute of Technology, Bombay.

Project Guide (Prof. Venkatesh Rajamanickam)

Internal Examiner (Prof. Jayesh Pillai)

External Examiner (Pratap Vardhan)

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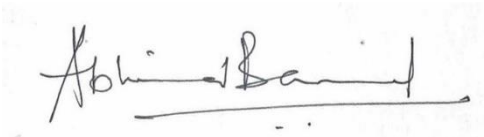

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Abstract

The project aims at explaining the concept of Deep Time and understanding the cause-and-effect relationships that led to the Evolution of Life by using interactive Data Visualisations. The visualizations are Exploratory and Data-driven in nature. Deep Time refers to the Life of the Earth, that is accepted to be 4.56 billion years in age. The human mind can easily visualize time-scales of smaller range (thousands to tens of thousands). However, as soon as this scale is increased, this understanding diminishes. I break down entire Geologic Time into 8 chapters and use a Narrative and a Metaphor of 80 years of human life to bind these chapters together. I design different visualizations for each chapter; however, the semantics were kept constant throughout. To understand the effectiveness of an interactive visualization, I conduct a Quantitative Evaluation where I gauge how many Data Points a user interacts with in each chapter. The results were tallied with the time spent by the user to see if any relation was found.

Contents

Introduction

Coined by John McPhee in 1981, "Deep time" refers to the **time scale of geologic events**, which is much greater than the time scale of human lives. Geological Time is divided into Eras, which is subdivided into Periods, that are further classified into 'Epochs'.

From the formation of the earth, to the present-day Holocene, the elapsed time is calculated to be roughly 4.5 billion years. To represent this on a piece of paper has been a challenge. One of the metaphors that John McPhee cited to explain the concept of deep time was:

Consider the Earth's history as the old measure of the English yard, the distance from the King's nose to the tip of his outstretched hand. One stroke of a nail file on his middle finger erases human history.

Humans have a hard time with really big numbers. Deep Time is one such concept. The history of the Earth took a lot longer than expected. The Holocene started roughly 12000 years ago as compared to the 4.5 billion years when the Earth was formed. (A fraction of 1/435000). The dinosaurs of the Mesozoic era ceased to exist 65 million years ago (1/692). This project aims at putting this time scale into perspective, while also exploring the relation between the timelines of events which led to the evolution of species on planet Earth. It would be interesting to note the changes in environment, geography and the evolution of species during individual eras. This project aims at making this information available to the masses in the most basic and interpretive way, using a series of analogies that culminate in a detailed visual representation of a large temporal dataset.

Aim and Objectives

The product aims to explain to the user a basic understanding of Deep Time, and how its evolution has made an impact on the environmental, geographical and economical resources on the planet through a series of visualizations; and thus, the evolution of life. Humans have been the protagonist for a mere 100,000 years (2.5 million years if we count the beginning of Homo Erectus). However, the evolution of earth has seen unfathomable changes, which are not yet adequately documented. I will be focusing on visual explorations and not on creating scientific data. Although, an expert validation would be conducted to verify the data that I shall be using. Since there are some debatable issues in the concept of Deep time, examples being the exact numerical time-line and the naming conventions, I would be using the most accepted ones, and would not dive into the discussions of these multiple options.

Overall, the broad objectives would be:

- Visualization of the different eras of the geologic timeline, and the various events, processes and facts depicted in them
- Visualizing the impact of the geological processes on the evolution of life of Earth

- Understanding the relationship of the environmental and geographical resources during these geological periods, if any and their impact on life.

Scope

I aim at creating a set of resources using an interactive article containing visualizations which would explain the users the evolution of earth. Representation of the Geological Timeline would be the primary resource. The project is meant for anyone who is interested in the concept of 'Evolution' in sciences, and is not merely targeted towards subject experts.

Further, the project may also be seen as a tool aimed at representing large time-lines (Huge numbers which are tough to represent both in the physical and digital space).

What the project covers?

- Attempts to narrate a cause-and-effect relationship between the various events throughout Geologic Time, that led to evolution of life on Earth
- Makes use of a Narrative & Interactive approach towards Data Visualization
- Does not attempt to justify any scientific concept or theory, but makes use of established theories

Methodology

I started by analysing existing literature for content curation and understanding the methods by which time has been historically represented. This is done by:

1. Knowledge Gather: Going through various books, peer-reviewed papers, articles, authentic documentaries and videos to understand the subject in-depth and prepare adequate content
2. Understanding Timelines: I conducted research to understand how large timelines are visualized, along with exploring the best tools which would help me represent them.
3. Understanding about the tools in visualization which help users retain the graphical knowledge

Following the preparation of the content, I started ideation based on individual encoding of data, and later I tried to combine multiple data sets into a singular visualization. Here, initially I explored different visualization techniques and tools for the same. A combination of digital sketching, scaled sketching using Graph Papers, and expansive interactive techniques were used. For the final product, given the time, I had to resort to a fully functioning Prototype of the envisaged website.

At certain stages, I also conducted some User Testing based on my ideations, and incorporated the feedbacks. Following this, I prepared

a baseline for the Usability Evaluation to gauge the success of the project. Main objective is to understand the impact the visualizations have made on the level of understanding of the users, and whether it helped generate more curiosity and interest about the subject matter.

Target Audience

The target audience for the projects were also the participants involved in User Testing and Evaluation. They are science enthusiasts, and not in particular Geology & Biology enthusiasts. However, they would be expected to have the following pre-requisites:

Should be interested in Science: The aim of this visualization is to generate curiosity in the minds of the users about certain subjects. The object is for them to only view this project for 30-40 minutes. It is expected that it encourages them to look into certain facts and processes that would be detailed in this project later on in their own time.

Literacy Level: High School (Class 10th) and Above: They should be familiar with Geography and Biology. It is expected that they know the terms such as Homo Sapiens, and are familiar with certain basic scientific concepts like Photosynthesis, Oxidation, Metamorphosis, Fossils

Tech Familiarity: The users should be familiar with certain interactive techniques like scroll, click and hover.

Literature Review

Understanding the Concept of Time and Temporal Data in Data Visualization

Temporal Data is a form of data that represents the state of time. Our understanding of time and temporal patterns is dependent on the lens we use, and data visualizations can provide a set of lenses for viewing time from different perspectives. For us to comprehend temporal data, the easiest way is to relate it with a measurable unit like 10 kilometres, 1 calendar year, 3000 steps etc. [1]

Time is believed to occur only when some events happen. Researchers like Benthem, Sergot and Hajnicz consider time to be composed of multiple events, which join together to form a structure, that is depicted by a phase of time. [2].

As per Hajnicz, time is represented by Point Time, and Interval Time. Recently there have been multiple attempts to represent time on a piece of paper (more specifically, on a 2D/3D surface) and digitally also. Hajnicz describes time to be comprised of three different notations: Facts, Events and Processes

Facts: Facts are individuals presenting a state of a described world, a represented reality. This notion is connected with everything which

is static and permanent in the world. These hold data of a 'single time moment'. If we look into Deep Time, the fact that Oxygen's composition in the atmosphere was 1.2% around 2 billion years ago is a fact. Some characteristics of Facts are:

- facts hold single time moments
- the period of time that determines the authenticity of a fact is called 'lifetime of the fact'. (McDermott, 1983) Without this lifetime, a fact is often unrepresented.

Events: If we think of facts as a static image of the world, then we can treat events as a dynamic image of the world. Events happen, and their occurrences initiate changes in it, i.e. in facts holding in it.

- Events are provided with sets of preconditions that have to hold in an initial situation in order to enable the event to occur (a question of feasibility of actions) and a set of effects (postconditions) that should hold in a destination situation.
- Eg. The Great Oxidation Event, which was triggered by the fact that 'presence of cyanobacteria on Earth rose around 3.2 Billion years ago.
- They hold multiple facts and have a lifespan (interval representation of time) and they occur in 'Time Intervals'

Processes: In a nutshell, processes trigger events, which lead to the formation of facts

- Processes are in some sense an intermediate notion between events and facts.
- Process is occurring in some initiating and some terminating subintervals of its occurrence interval in time. [3]
- Therefore, processes can cause changes in facts, other processes (rock decay causes decrease in volume) or even events (growing old causes death.) [2]
- An important class of processes is that of physical processes. It contains the movement of objects, the flow of liquids, changes of temperature etc. These processes are continuous.

Hence, whenever we represent Time, we need to represent the Facts, Events and Processes which have happened during that particular period/ interval of time.

An event that has been going on throughout the Deep Time is the constant changing of earth's composition. Since 2.5 billion years ago, the Event of 'Evolution of Life' is happening. This event was triggered by the process of Release of O2 by Cyanobacteria through Photosynthesis. Hence, we come to another conclusion. Events may have Sub-Events, which may trigger Processes. Example- The Great Oxidation Event triggered the Evolution of Life on Planet Earth by releasing oxygen into the atmosphere. [4]

Characteristics of Time Series Data

Time series data refers to data with time attributes that change over time. Thus, time series data has both time (the period) and data attributes (the facts). [5]. This corresponds to the literature works done by Hajnicz, where she breaks time into facts, events and processes, as described earlier.

There are three main ways to characterize time attributes:

1. **Linear Time and Cycle Time:** Linear time means that the time from the past to the future is linear. [5] I infer this represents a single event which is going throughout its lifespan. The cycle time refers to the cycle, where multiple linear times co-exist and repeat to form a cyclic time. Eg. The change of seasons, the rainwater cycle, predator-prey relationship.

2. **Time points and time intervals**: The time point corresponds to a discrete time point, and the time interval is a small linear time domain.

3. **Sequential time, branch time and multi-angle time.** Sequential time refers to events occurring in chronological order, and branch time refers to multiple time branches originating from the same point. Linear Times can act as different branches of this representation of time.

Thus, before visualizing any sort of temporal data, it is important to highlight its attributes i.e. the facts, events, processes and the linearity which it follows. Based on the acquired Data Type, they are divided into low-dimensional and high-dimensional features. These characteristics form the base of a Temporal Visualization. [5]

How Humans Understand Time

To further depict time as visualization, I tried to understand how humans perceive time and whether it is possible for humans to even comprehend big time.

Historically, the perception of time by humans is based on lifespans of commodities and humans alike. McPhee, in 1981, states that once we move into hundreds of thousands of years, or even millions or billions of years, we try to comprehend this information on the basic of abstractions. He also proposed ratio-based heuristics as a measure of comprehending big timescale, and thereby big numbers. This is where metaphors play an interesting role, as they are able to narrow the entire timescale into a smaller, experiential domain that is easily visualised by most of the population.

Even though we don't experience the entirety of a lifespan, evidences in the form of elderlies and their accounts around us act as examples. We can now use their lifespan as a template to measure larger timescales around us. This ends up acting as a unit of measurement and a temporary scale for the humans to perceive any

timeline. [1] A span of 60-100 years, thus becomes the basic unit of measuring time in a large time scale.

The events and facts, like technological advancements, memorable events and historic events act as mediums which populate this time scale. Greater the quanta of these events, the larger the time scale is perceived by us. Multiple users, when asked about their perception of time, related it with the happening events during that time. Many of them consider the 2 years of Covid-19 pandemic as non-existential, since nothing really happened during that phase in their lives.

Historic Representation of Time

Tufte, in his book Envisioning Information states that depicting four-variable narrations of space-time onto flatland combines the designing of two historic representations of time: the map and the time-series. [6]

Corkscrew Diagrams (Fig.1), Strip Maps, Time-tables and Indexed Route Maps are some of the ways in which attempts have been made to visualise this 4-dimensional data on a 2D plane. It is important to understand that the encoding which is done, does not hamper the information density and the type of information, which is often presented in a multi-variable narrative. [6]

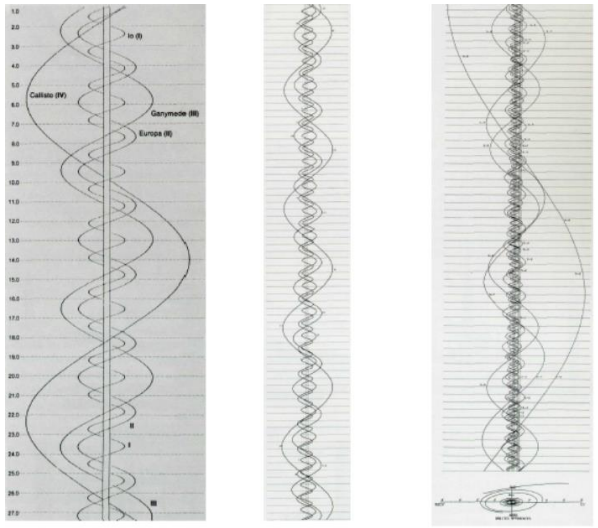


Figure 1: Corkscrew Diagram of Jupiter's Satellite (Source: Envisioning Information, Tufte)

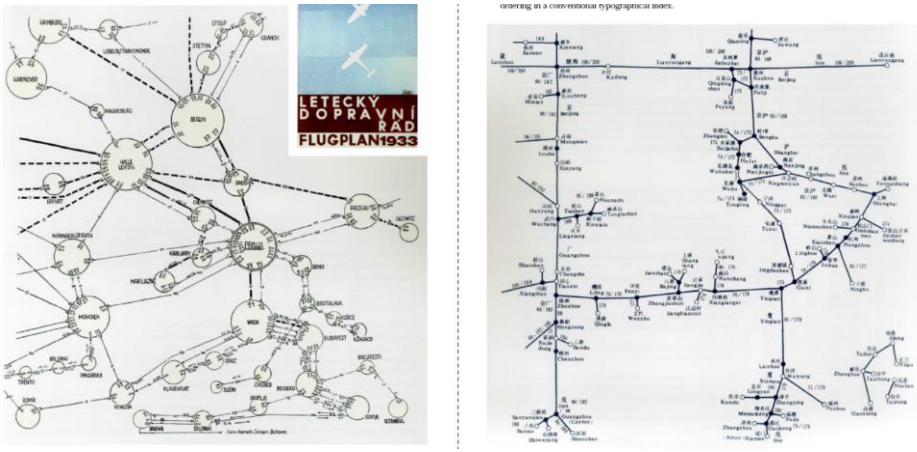


Figure 2: Representation of large time tables and time lines (Source: Cartographies of Time)

Graphical timetables (Fig.2) (of historic rail routes) compress the dimensionality of data by measuring distance along the rail line itself, converting three-space reality into a path on paper.

In one of the earliest representations of Deep Time, Stapledon represented Deep Time using a series of different scales (Fig. 3). The representation of time in 'The Last and First Men', shows 11 vertical lines drawn to the scale of 1:4, to 1:4,000,000,000. Although the immediate relationship between consecutive scales was apparent, the relationship between the first and last scale is not easy to grasp. [7] This technique is excellent to show immediate relationships, but the scales of events end up being misrepresented in the longer run.

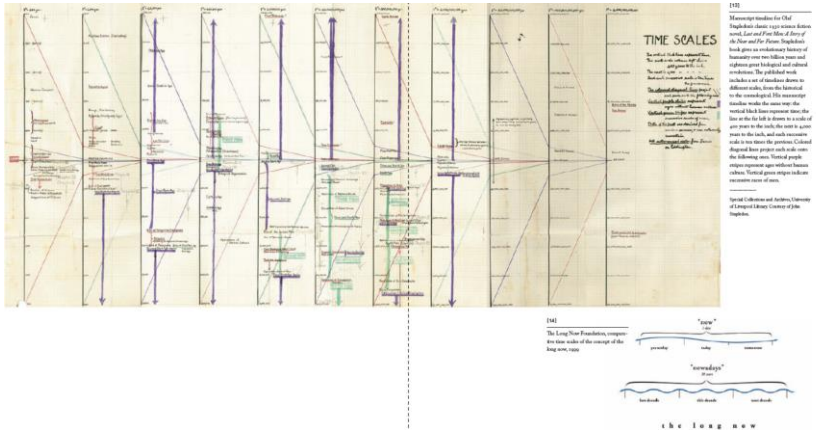


Figure 3: Representation of Deep Time by Stapledon (Source: Cartographies of Time)

One of the earliest forms of interactive physical visualizations of chronological data, emerges in the form of Discus Chronologicus (Fig.4) (Chronological Disk) by Christoph Weigel around 1723. [7] The layout is circular, with rings representing kingdoms and radial wedges representing centuries. The names of the kingdoms are written of the movable arm, that can be repositioned as per the needs. Here, equidistant wedges are being used to depict the axis of time.

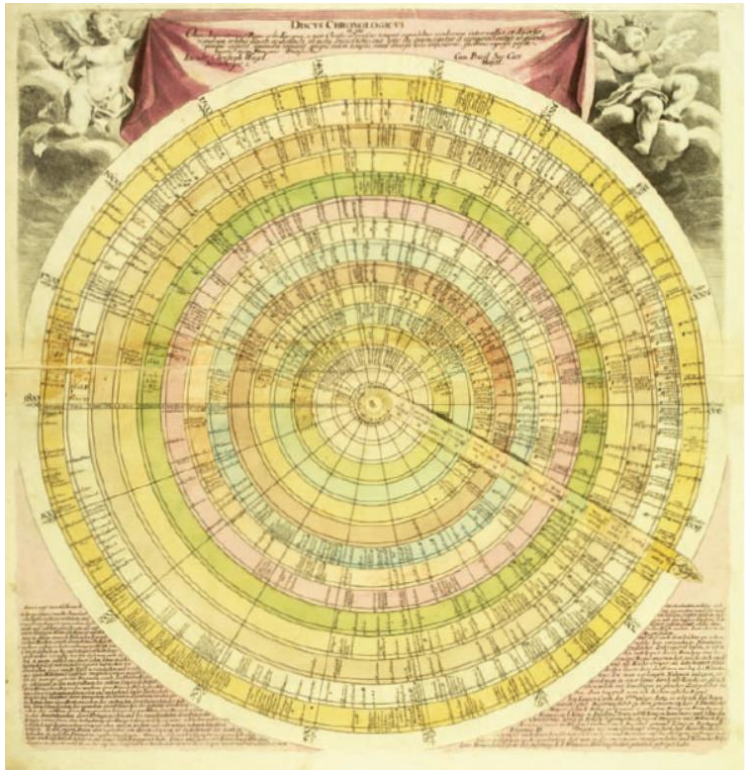


Figure 4: Visualization exploring Circular Timeline. This was one of the first visualizations to have an interactive medium (the hand could be moved). Source: Cartographies of Time

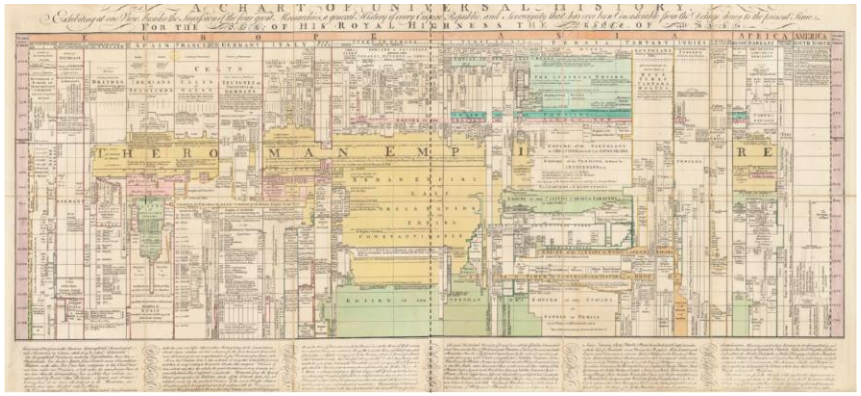


Figure 5: Chart of Universal History, Thomas Jeffrey, 1750 (Source: Cartographies of Time)

In 1750, Thomas Jeffery released A Chart of Universal History (Fig.5) that used cross referring on Horizontal and Vertical Axis as a premise to depict chronology. Here, the nations are named in a row at the top of the page, while dates descend in a column. Entire Chronology is displayed on a single, continuous plane, and the scale of the empires is encoded using different colors. Visually, the areas highlight the expanse of the empires, which also match the timescale as mention on the horizontal axis. This was one of the earliest attempts at mapping Temporal Boundaries of Historical Entities and Events. [7]

Gradually, this visualization paved way to an integrated study of causes, relations and effects of events in a large time scale. These were now internally referenced (within the visualization), an approach that was adopted in the depiction of chronologies in the 18th and 19th century.

Although representation of chronological data was evolving, eminent figures like Priestley, Strass and Jeffrey believed that a graphic representation of history held advantages over a textual one, since they revealed order, scale and interdependency (synchronism) more effectively, in a single domain. [7] Thus, it removed the trouble of memorization and calculation. However, some critics believed that that uniformity in the linearity is misleading.

Use of Metaphors in representation of Time

Reinforcing on the words of McPhee, that large time scales are better represented by Ratios and metaphors by making unique measures of temporal visualizations. They help the human brain to scale down unfathomable numbers, to relatable scales, by compressing the data using a defined ratio. Sekulak et al describe this time as Psychological Time, or the mental representation of time. [8]. The Cosmic Calendar, by Carl Sagan is one such representation, where the entire time span of the universe is compressed into one Calendar Year of 365 Days.

Timeline is described by many as an information visualization tool for communicating a sequence of related events. Keywords being Sequence, and Related. When analysed, a timeline can support the Time is Space metaphor as described by Lakoff and Johnson in 1980. [9] Proximity in Time is Proximity in Space is thus obtained. Lakoff

further states that arrangement of events as objects along the timeline can be seen as an instant of objects being mapped on any structured metaphor.

However, with this being established, it is important to create a metaphor that is relatable to the users, and not beyond their imaginations. Knowing this, I tried to find metaphors of two distinct typologies:

1. Time being used as a metaphor of time
2. Time being used as a metaphor of Space, where time units are converted into spatial units, thereby enabling translation of time into space.

Time being used as a Metaphor of Time

The Cosmic Calendar(Fig.6), by Carl Sagan is the best example of time being used as a metaphor of time. He compresses the 13.8 billion years age of universe into one calendar year of 365 days. Every duration is represented in Cosmic Seconds, Cosmic Minutes or Cosmic Hours. In this cosmic calendar, on 1 year, an extended human life of 100 years lasts only 0.23 Cosmic Seconds. Another interesting thing to note in this representation is the use of different scales to represent populated events, albeit, the scale of 'Cosmic Seconds' has been kept constant. To keep authenticity, Sagan also highlights the evidences which lead to discovery of important dates within the representation. Despite the latter portion being given more significance in the overall scheme of the representation, this mathematical conversion and representation of the cosmic time-scale for every event manages to bring in a sense of scale and expanse of time.

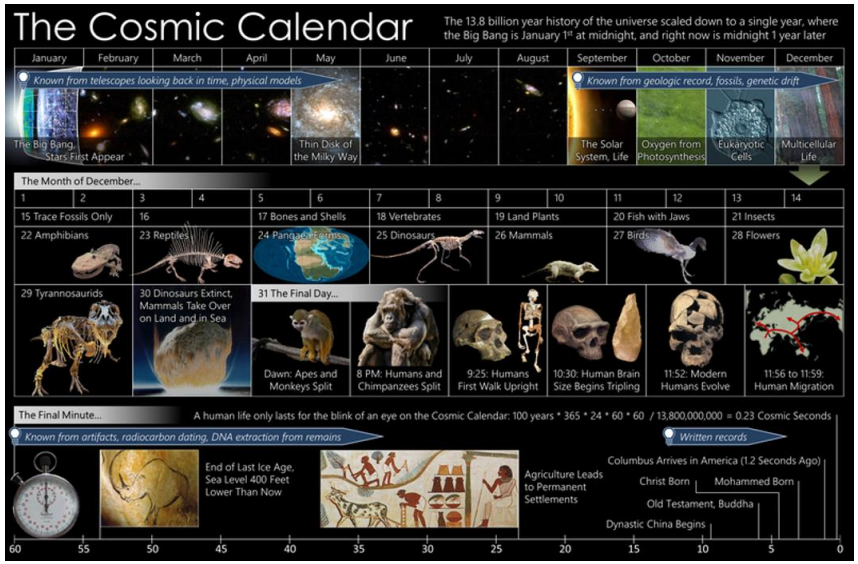


Figure 6: Cosmic Calendar by Carl Sagan

Time being used as a Metaphor of Distance

Time as a Metaphor of Distance has been explored in many means. It can be related to the physical size of objects, or even as a physical narrative. The Deep Time Walk generates one such experience, where the user is narrated the entire history of earth. In a walk comprising of 1.5 hours, and roughly 4.5 kilometers, the final half-step is supposed to represent 300,000 thousand years of human existence. Thus, an experience has been created, which informs the

users about the events of Geological Time, while keeping the scale of events intact. Randall Munroe's information graphic of compressing the Geologic Time into the height of Mount Everest is another such example. In his depiction, the human span on earth is smaller than the size of an ant.

Metaphors and Scales

Metaphors thus enable the users to understand the sense of scale in a more comprehensive manner, by relating them to something which can be experienced by them. Something that certainly cannot be understood by adding 0s behind a number. However, it is important to cite metaphors that are relatable to the users. Example:

- 10 metres wrt 7 times distance of the earth is a bad metaphor
- Thickness of a human finger wrt height of the Mount Everest is a better metaphor
- A speckle of dust on a 400m Olympic track is better, but some facts can get insignificant in such a case.

To conclude the usage of metaphors, using what we know if a good way to make people visualize large numbers. Some highlights are: [10]

- Use Time and Distance parallelly
- For most, millions, billions and trillions are "big". They are not intuitive
- Metaphors are seemingly the best way to make people understand the sense of scale
- Developing a sense of scale helps us convey that understanding in a better way.

An example for this would be: [10]

- 1 second is 1 second
- 1 million seconds is 12 days
- 1 billion seconds is 30 years
- 1 trillion seconds is 30,000 years

Data Collection for Deep Time

Wang and Hazan, in a 2021 paper talk about establishing an open-source Data base to help understand Deep Time. To fully understand the concept of Deep Time, one must understand 4 major geological components: [11]

- Evolution of life and biodiversity:
- Evolution of Earth materials
- Evolution of geography
- Evolution of climate

For this purpose, I read Geological Sciences Books in Detail. (Earth System History, Babcock & NG, Earth's Evolving Systems) and also read novels like Dawkins' Our Ancestor's Tale and The Story of

Earth by Robert Hazan. Together, I made a timeline that supported the events which have taken place on the planet since 4.5 billion years. (Link to Data Set in Google Sheets)

Geologic Time/ Source	Timeline	Start	End	Notes	Earth Conditions	Geology and Atmosphere	Life Conditions	Specie Notes	Continents	Key Words
Hadean and Archean	0	4500	2500	The Archean Eon (Figure 8.1) begins with this planet's formation, approximately 4,567 billion years ago. The end of the Archean is automatically defined by the beginning of the next eon, the Proterozoic Eon, a point chosen as 2.5 billion years ago.	Crust full of Silica. Only Volcanic Surfaces existed.	Early Earth was MOLTEN only.	None	None	None	
		4480		Early Melting Produced a Layered Earth, Solidification of Magma was happening as earth was rapindly colliding with Meteors and other Galactic Objects, which solidified to form the crust.	Differentiation of Earth due to variation in Density					
		4480	44507	Formation of Internal Layers of Earth, around the Core		Komatiites and Basaltic Rocks formed on cooling of the Earth's surface.				
	60	4440		Formation of Moon, from a pseudo-earth called Theia						Conservation of Angular Momentum
	100	4400		Formation of the Basalt Crust on the Surface of Earth	Basalt Crust, no Water					
	129	4274		Zircon Crystals found for detecting age of earth using Uranium Half Life Dating						
	150	4350		The Blue Earth. Formation of Oceans now take place	Water is only 0.02% of the Earth's mass at this moment	High percentage of O18 in Zircon Crystals show that this oxygen must have come from water only as the lighter O16 would have evaporated				
	200	4300	4000	The formation of a Granite Crust						
	500	4000	3800	Formation of a greenstone belt of the Acasta Gneiss of the Slave craton in northwest Canada - the oldest known rock belt.	Formation of Greenstone Belts				Present day Canada	
				One group of sedimentary rocks, called banded iron formations, or BIFs, are almost completely restricted to the Archean and Proterozoic						
	600	3800	2500	Cells resembling prokaryotes appear. These first organisms are believed to have been chemoautotrophs, using carbon dioxide as a carbon source and oxidizing inorganic materials to extract energy.			Earliest Living Organism in the form of PROKARYOTES appear	Prokaryotes ONLY		
				Nevertheless, based on the fossil record, life arose no later than about 3.8 billion years ago. Primitive life is surprisingly resourceful and resilient. Certain bacteria live at temperatures ranging from well below freezing to above boiling, and most recently have been found living deep within Earth's crust.			Single Celled Organisms Only Archeabacteria	Archeabacteria, surviving on minerals like Iron		CHEMOSYNTHESIS: Process of existing through synthesising energy from oxides and chemicals.
				Those earliest microbes simply learned chemical tricks that Earth already knew.						
				most major groups of Bacteria and Archaea of the modern world may have appeared before the end of Archean time. Several types are known to have existed by about 3.5 billion years ago.					Western Australia, Greenland	
	1000	3500		Cyanobacteria are likely to have been the photosynthesizers. Oldest Fossils of Cyanobacteria have now been found		Stromatolites in Western Australia suggest that photosynthesis was occurring by about 3.5 billion years ago				

Figure 7: Data set taken from the above-mentioned sources

Evolution of life and biodiversity

Understanding the patterns of life helps us understand the cause-and-effect relationship between non-living materials which lead to the evolution of living entities. This includes understanding timing of biological extinction and diversification events, and relationships between environmental changes and biodiversity fluctuations, and also the features that thus developed.

Evolution of Earth materials

Earth Materials like oceans, landmass, soil and sediments often dictates the distribution of life, and vice- versa.

Evolution of climate

Climate directly affects events such as extinction, and also leads to evolution patterns in the species. Example: The lowering of sea levels led to the plants surfacing on the land for the first time, and thus developing a vascular system to extract nutrients from soil.

Evolution of geography

This includes tectonic reconstruction and mineral expansion throughout the planet's history. Although it does not directly affect life always, it contains evidences of shift in living patterns.

In this project, I mainly focus on the first three elements, as records of Geography are still under examination and development and would go beyond the scope of the project. Even in the first three components, I would be limiting myself to certain data-sets only keeping in mind the duration of the project.

Need for Re-Design: Critique of Existing Work on Deep Time Visualizations

Deep Time (1975) by National Geographic

Figure 8: Deep Time Spiral by Joseph Graham, William Newman and John Stacy

One of the earliest representations of Deep Time, the information graphic mainly focusses on the post-Cambrian period, starting 542 Mya, where life became abundant. However, the representation of time before that period is not very adequately done.

Once can sense the expanse of time, but it is not possible to understand the conditions of Earth before 542 Mya. The main focus here is on life, and that is very well represented. The choice of Spiral also resonates with never ending time.

In this visualization equal importance is not given to all the time periods of Geologic Time. However, to understand Deep Time, it is important to learn form the events of the past and related them with the near-past and present events.

OneZoom Tree of Life Explorer

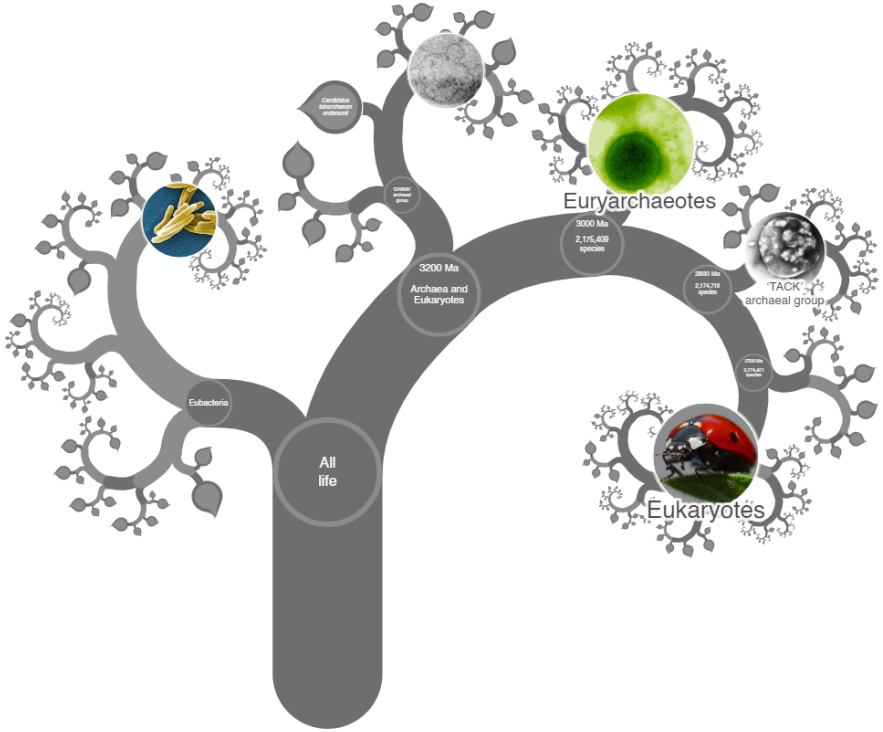


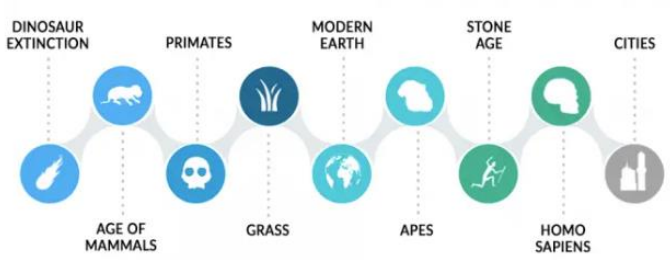
Figure 9: OneZoom Tree of Life

Accessible at (onezoom.org; as on Nov 15, 2022), this is an interactive map of the evolutionary links between all living things known to science. Starting from the Archaebacteria, one can zoom into any branch of the magnificent tree of life. This is a very comprehensive resource that slowly unfolds all the connections of life through selective zooming.

One of limitations are that the relationship between different species are not easy to understand in such a method of zooming. Further, this only represented the life forms on Earth and the geologic and atmospheric elements were missing.

Although importance to past life is given, one is unable to relate it with the present since the exploration consumes a lot of time. There is a lot of data present in this that definitely caters to the requirements of domain-specific users, but is not captivating for general audience (targeted audience).

Website: Earthhow.com



1. The dinosaurs went extinct

Ultimately, the start of the Cenozoic Era was the demise of dinosaurs. After a 6-mile wide asteroid hit Earth 66 million years ago, a dust cloud blocked the sun. It was the Cretaceous–Paleogene (K-Pg) extinction event that wiped out the dinosaurs.

The worldwide climate disruption caused temperatures to plummet and enter an ice age. Because of the reduced sunlight, it halted photosynthesis from plankton and plants.

Figure 10: An article on EarthHow

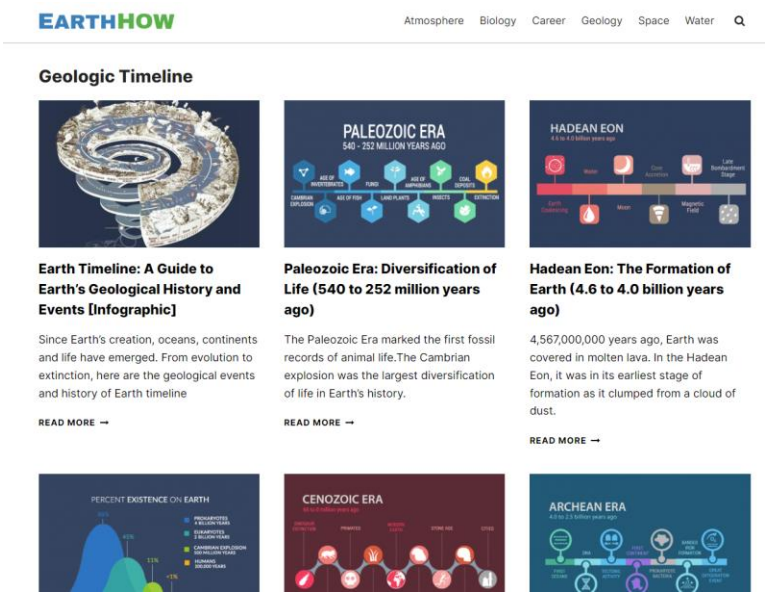


Figure 11: Homepage of Geologic Time Section of Earthhow.com

Accessible at (Geologic Time, as available on November 15, 2022), this is an online repository containing a series of articles of different periods of Geologic Time. All of them are supported by Visuals and Diagrams to make the text relatable for the user.

This repository is well suited as an instructive course to Geologic Time. However, a seamless transition through time is missing. Further, I found that many important facts and pivotal moments in time are missing in this resource, presumably in an attempt to not

overload the users with information. The key takeaway was how small visuals can support my narrative.

Application: Deep Time Walk

Deep Time Walk (Fig.12) is an immersive mobile application of Deep Time, where the users are encouraged to go on a walk. The facts are narrated using audio. Learnings from this was how metaphors can be used to make an instant impact of the scale of time.

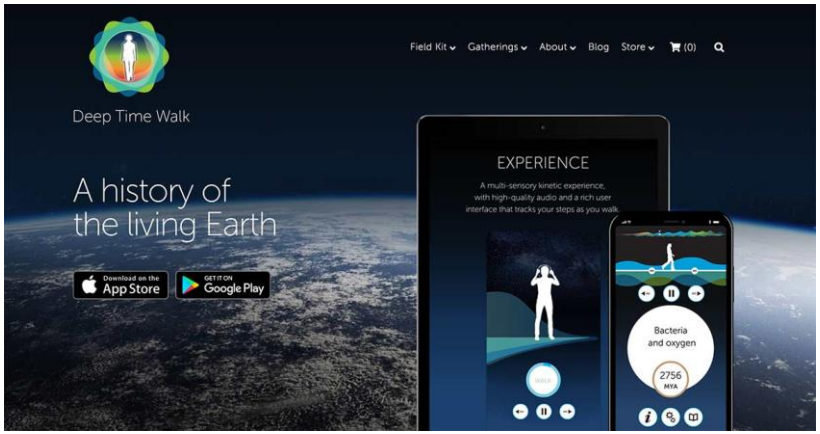


Figure 12: Deep Time Walk Homepage (Source- deeptimewalk.org)

Novelty in the Project

Although the primary means of data is the set of interactive visualizations, a narrative-based approach is adopted to bind the visualizations together (Story Telling). The project uses a combination of story-telling to support the visualizations. This enables users to constantly relate the large time-span with a relatable figure (via the use of a metaphor). A story-telling based approach would also help in generating curiosity in the minds of the users throughout their journey. This would encourage them to explore the given data even further. Story telling would also help in the positioning of the data in the different intervals of time.

Exploratory nature would give the users a certain degree of freedom, and they can explore the visualizations that they want to. The main objective is to keep the users waiting for the next set of visualisation and slowly unfold the insights of research. Every chapter (Set of Visualization) is curated in such a manner that the user spends maximum time in the phase the holds the most important Geologic Events. This distribution of time, and thus interest was important.

However, it was ensured that the story does not take the centre-stage. Hence, it was kept minimal. Two layers of narratives were added- the first as an overview of the chapter (time-period), and second as interactive data sets.

Curating the Narrative

The protagonist of the Story is a being with a lifespan of 80 years (relatable to the human life). The Geologic facts and events are the incidents that this being has observed throughout its life. Although it comprises of scientific facts, a simplified explanation has been used throughout, keeping the authenticity of the facts/events intact.

The metaphor of 80 years of human life was preferred over a shorter span or a distance-based metaphor because:

- In a 1-year narrative, the time of earth (1 year), wrt time of Humans was 1 year: 3 seconds. Hence, the latter segments of the Geologic Time (specially the last 5 years) were all very close to one another to differentiate.
- This was helped by taking the time span to 80 years, when the Last 5 million years got reduced to 1 month, and last 12,000 years (Holocene) to a few minutes, and the Human Life (80 years) to 45 seconds.
- Using the metaphor of Time instead of Distance reduced the cognitive load on the users. In the initial User Testing, pauses were observed to relate time with distance.
- It is a relatable scale because even if the audience has not experienced 80 years, they are familiar with people around them who have lived this long. They have heard their stories and developments in life.

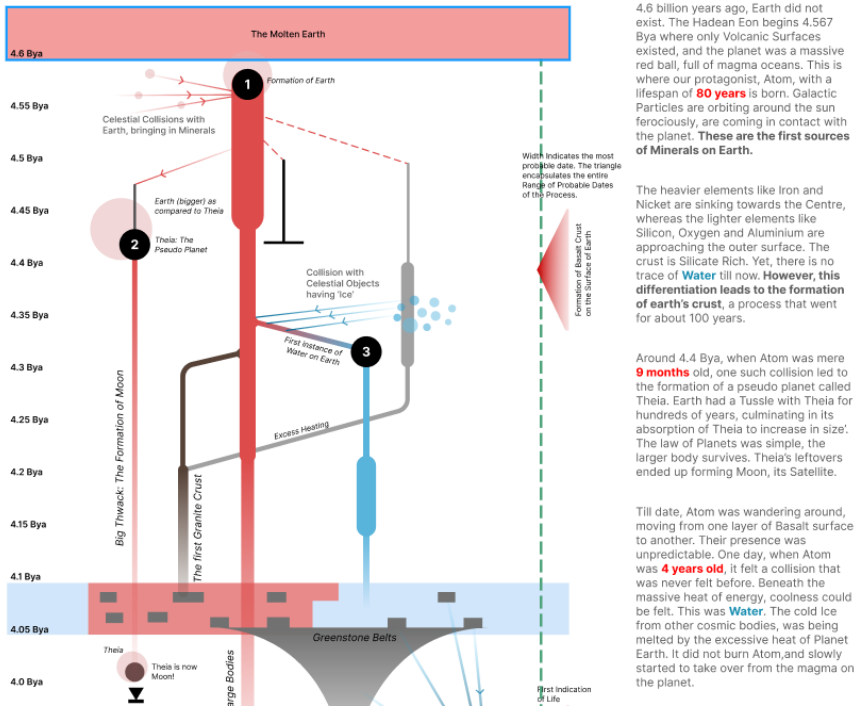


Figure 13: Initial Ideation of Visualization along with Story

Phasing the Narrative into Chapters:

The chapters in the narrative were not based on time, but based on Important events that have happened throughout the Geologic Time.

During the User Testing it was observed that the names of Geologic Periods held no importance to the users. It was important to make them understand that the events that have happened in the last 100,000 years are equally important to those that have happened in the early 1 billion years. The pace with which changes are happening in today's world is rapidly increasing. The chapters were divided as follows:

Chapter 1: The Hadean
Geologic Time: (4.56 Billion Years Ago to 4 Bya)
Metaphor Time: (80 years to 71 years)

This introduces the user to the Geologic Time, that begins with the Hadean period and finished right at the onset of the first indication of life. It reflects the early atmospheric and surface conditions of the earth and how they set up the stage for life.

Chapter 2: The Hadean
Geologic Time: (4 Bya to 2.8 Bya)
Metaphor Time: (Next 21.5 years; 30.5 years of age now)

This talks in detail about the changes that happened which led to the formation of life. This ends when the conditions are set for Earth to have its first taste of 'Atmospheric Oxygen'.

Chapter 3: Life's Cooking
Geologic Time: (2.8 Bya to 1.8 Bya)
Metaphor Time: (Next 18 years; 48.5 years of age now)

This chapter introduces Atmospheric Oxygen and how it led to formation of the earliest ancestors of plant and animal kingdom. Life now evolves from Prokaryotes to Eukaryotes. This eventful stage ends at the onset on the most boring stage of Geologic Time.

Chapter 4: Boring Billion, yet Rodinian
Geologic Time: (1.8 Bya to 542 Million Years Ago; mya)
Metaphor Time: (Next 22 years; 70.5 years of age now)

This chapter, less data inducive talks how Earth had achieved a sense of stability. However, certain events at the end of this phase led to the biggest change Earth had yet seen; the Cambrian Explosion- the onset of Life. At this stage the user also realises that significant life still doesn't exist, despite 71 out 80 years having passed.

Chapter 5: Boom! Explosion of Life
Geologic Time: (542 Mya to 65 Mya)
Metaphor Time: (Next 8 years; ~ 79 years of age now)

This chapter talks how Life Came, survived, evolved, caused environmental changes, led to extinction, survived again, adapted and evolved. This ends at a significant moment- extinction of Dinosaurs- presumable the only well-known extinction events known to the audience.

Chapter 6: Bye Bye, Dinosaurs!
Geologic Time: (65 Mya to 5 Mya)
Metaphor Time: (Next ~12 months; 79 years 11 months of age now)

Here, we learn how they demise of the great predator (the dinosaurs) led to a rapid growth in the evolution of mammals. This in turn led to multiple levels of diversification in plants. Together, they have started causing mass extinction rapidly. Note- all these things till now are natural, and humans are yet to enter the scene.

Chapter 7: The Hominid Appears
Geologic Time: (~6Mya to 300,000 years ago)
Metaphor Time: (1 month left till present from 80 years)

The appearance of Hominid Family and the subsequent evolution into Homo Sapiens is covered. It also talks about events of domestication, tool making etc.

Chapter 8: Ape Becomes a (Hu)-Man
Geologic Time: (250,000 years ago to Present)
Metaphor Time: (The final 1.25 Days)

The Humans finally appear on the last day of the journey. Our present calendar takes an estimated 5 hours in this entire Timespan of 80 years. And the lifespan of 80 years? It is mere 47 seconds. The changes that happened over roughly 5 years earlier, are occurring every 4 seconds. Such is the cause-and-effect relationship within the Deep Time.

Finalizing the Data

Before starting up with Encoding strategies, it was important to define the scope of the Data that would be represented. I took cues from the existing work and the template as described by Wang et al, as mentioned earlier. The following data was to be encoded.

Paleogeography: This would contain the landmass locations on the planet at critical intervals of time. This can be encoded via schematic maps that are processed using a slider (Fig 14). In encoding, various types of lines with different thicknesses can be used.

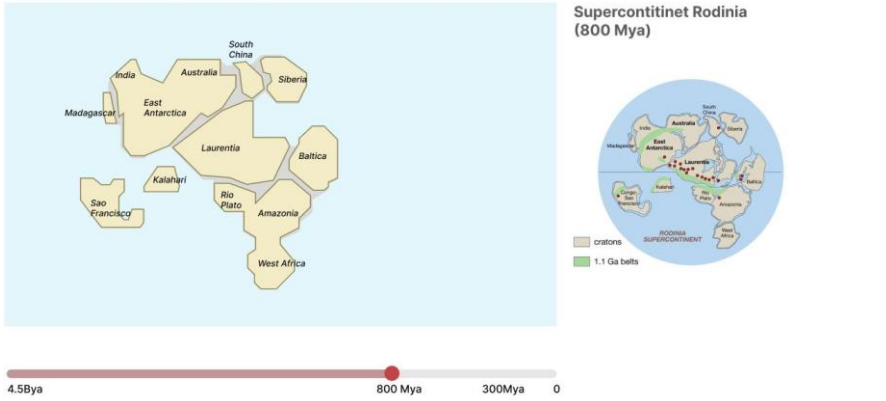


Figure 14: Schematic Representation, with the source image on right. The slider having time markers is also shown

Main Human Line of Evolution: Out of multiple evolution branches in Life, I would focus predominantly on the Evolution of Humans i.e. How did the Hominid genus (and eventually Homo Sapiens and Neanderthals) evolve from the Universal Ancestor of Life. There have been multiple evolutionary changes (approx. 30, as described by Richard Dawkins in his book The Ancestor's Tale) that led to the formation of the family 'Hominoids' from the LUCA (Last Universal Common Ancestor). It ranges over 3.8 billion Years. It would be important to understand this evolution, and how it differentiated at different intervals of time.

Representation of Kingdoms of Plants, Bacteria and Animalia, which are connected in the process of Evolution of Life: It is important to understand how corelation, and cause-and-effect caused these kingdoms to evolve and decline in the nature. Some relationships like 'Predator and Prey', and Domestication are of utmost importance. For the Scope of the project, all of the Evolutionary Changes would not be depicted. However, the most critical ones, as defined in the previously mentioned books and in the IUCN List shall be taken into context (Fig 15).

For the scope of this project, however, they would not be fully detailed out, but their point of origin in the geological time would be marked as accurately as possible.

	Estimated Number of described species[1]	Number of species evaluated by 2022 (IUCN Red List version 2022-1)	% of described species evaluated by 2022 (IUCN Red List version 2022-1)	Number of threatened species[2] by 2022 (IUCN Red List version 2022-1)
VERTEBRATES				
Mammals [5]	6,577	5,969	91%	1,337
Birds	11,162	11,162	100%	1,409
Reptiles	11,690	10,150	87%	1,845
Amphibians	8,463	7,316	86%	2,515
Fishes	36,248	24,356	67%	3,548
Subtotal	**74,140**	**58,953**	**80%**	**10,654**
INVERTEBRATES				
Insects	1,053,578	12,161	1.2%	2,291
Molluscs	84,528	9,017	11%	2,384
Crustaceans[6]	80,122	3,197	4%	745
Corals	5,574	846	15%	232
Arachnids	110,615	441	0.40%	251
Velvet Worms	210	11	5%	9
Horseshoe Crabs	4	4	100%	2
Others	157,543	904	0.57%	152
Subtotal	**1,492,174**	**26,581**	**2%**	**6,066**
PLANTS [7]				
Mosses [8]	21,925	282	1.3%	165
Ferns and Allies [9]	11,800	747	6%	288
Gymnosperms	1,113	1,046	94%	436
Flowering Plants	369,000	59,222	16%	23,551
Green Algae [10]	12,382	16	0.1%	0
Red Algae [10]	7,480	58	0.8%	9
Subtotal	**423,700**	**61,371**	**14%**	**24,449**
FUNGI & PROTISTS [11]				
Lichens	17,000	86	0.5%	62
Mushrooms, etc.	120,000	511	0.4%	222
Brown Algae [10]	4,485	15	0.3%	6
Subtotal	**141,485**	**612**	**0.4%**	**290**
TOTAL	**2,131,499**	**147,517**	**7%**	**41,459**

Figure 15: Most prominent groups of species as identified by IUCN in the Animal, Plant and Fungi kingdom

Representation of Climate: Climate plays a very important role in dictating the growth of species. Factors such as Rock Constitution, Oxygen & Carbon-dioxide Levels, and Sea Levels especially can act

as parameters of growth and destruction. It was also observed that majority of the extinction events actually happened due to a radical shift in such parameters, which in turn caused a change in the Predator-and-Prey relationship of the species.

Visualization: Simple Line Graph, Coloured Charts and Sun Burst Diagrams

Representation of Events: Lastly, it is important to mark out some important events which have happened throughout. These events include, but are not limited to the Formation of Oceans, Formation of Moon, Formation of Land and certain Glacial Events that changed the way species evolved.

Visualization Ideations

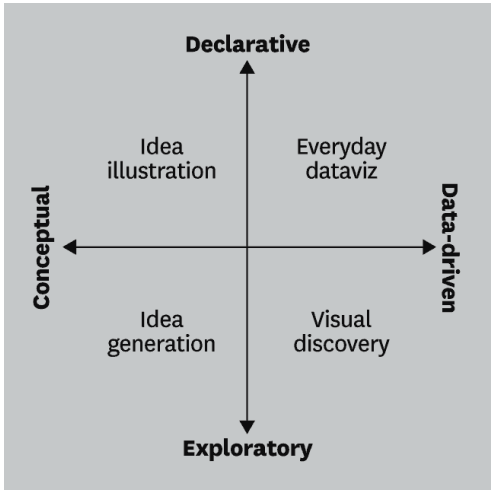


Figure 16: Type of Data Visualizations as described by Scott Berinato

Timeline Visualizations

The initial visualisation mainly covered the Idea Illustration (Fig 17) aspect, since it was Conceptual and partly declarative. It also involved the reliance over a Metaphor to convey the idea properly to the users. As per Scott Berinato, in this type of visualisation, the focus should be on clear communication, structure, and the logic of the ideas. [12]

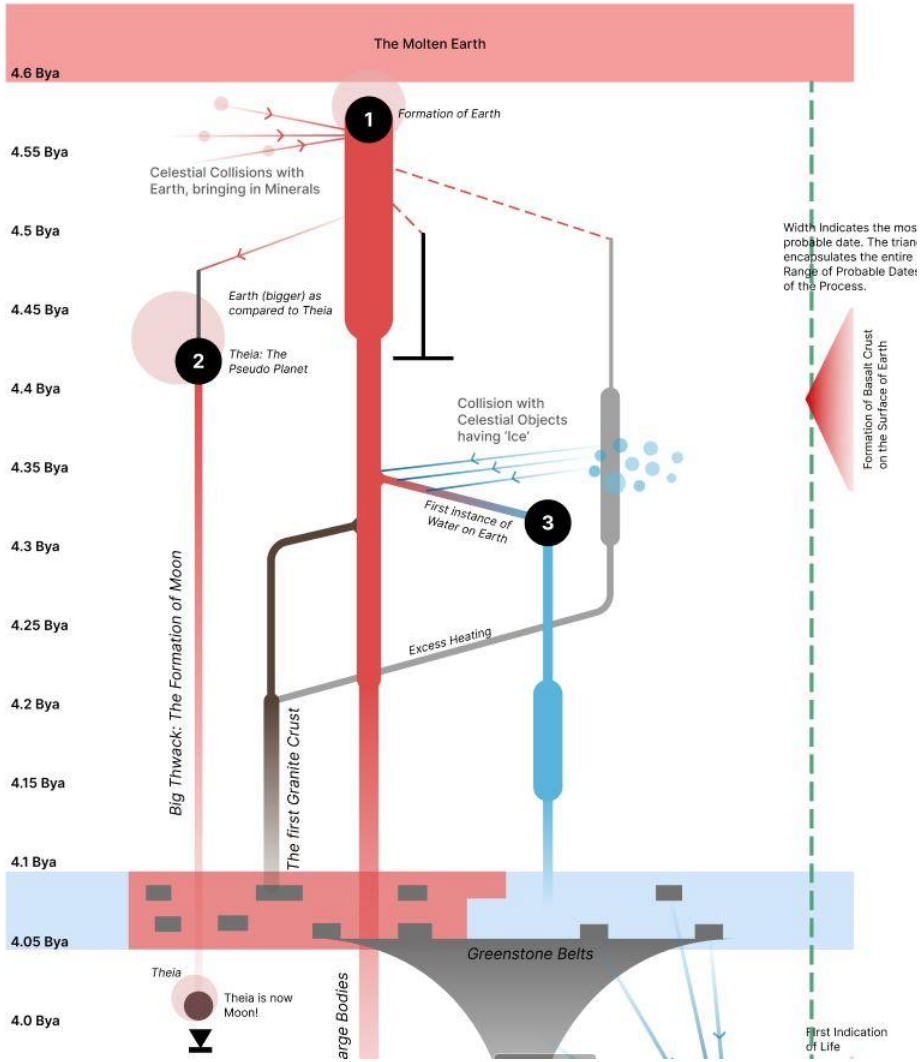


Figure 17: Exploring a Linear Vertical Timeline that serves as a visual narrative (Conceptual and Declarative)

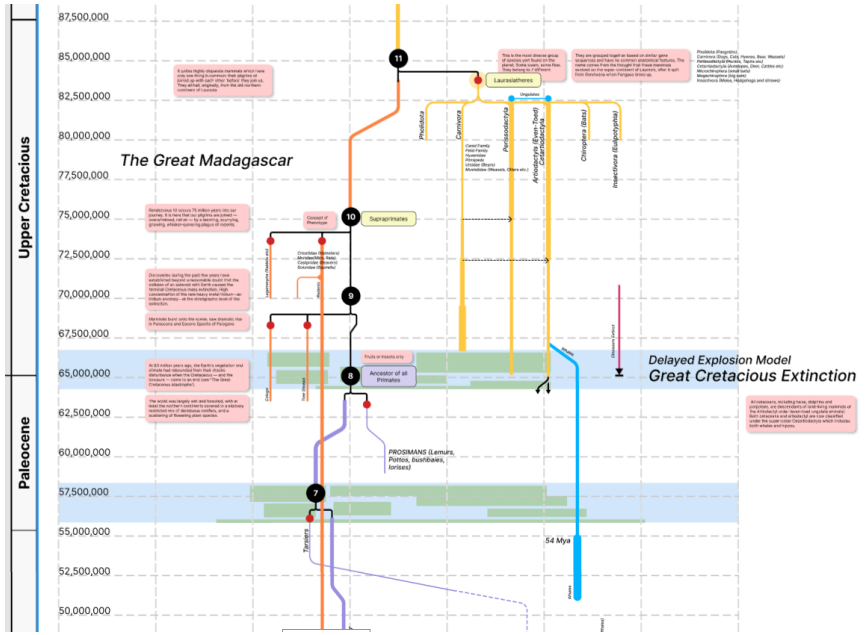


Figure 18: Initial Ideation of using Encoding strategies in a Linear Timeline

The next iteration (Fig 18) involved encoding principles. Colour represented one particular group of species. The 'Black' Circular numbered Nodes highlighted the evolution into different taxonomic groups (Example separation of gorillas from chimpanzees in more recent times; separation of Amphibians from Reptiles in earlier times) that directly led to the formation of 'Hominids'. Homo Sapiens further evolved from Hominids. This represented the idea of a Visual Discovery, that was exploratory in nature.

The Red dots indicate the same changes, but for species that did not result in evolution of Hominids. However, these played in important role in the ecological system. Eg: Evolution of Insects and Grazing

Species led to the evolution of Angiosperms (flowering plants) and Grass respectively.

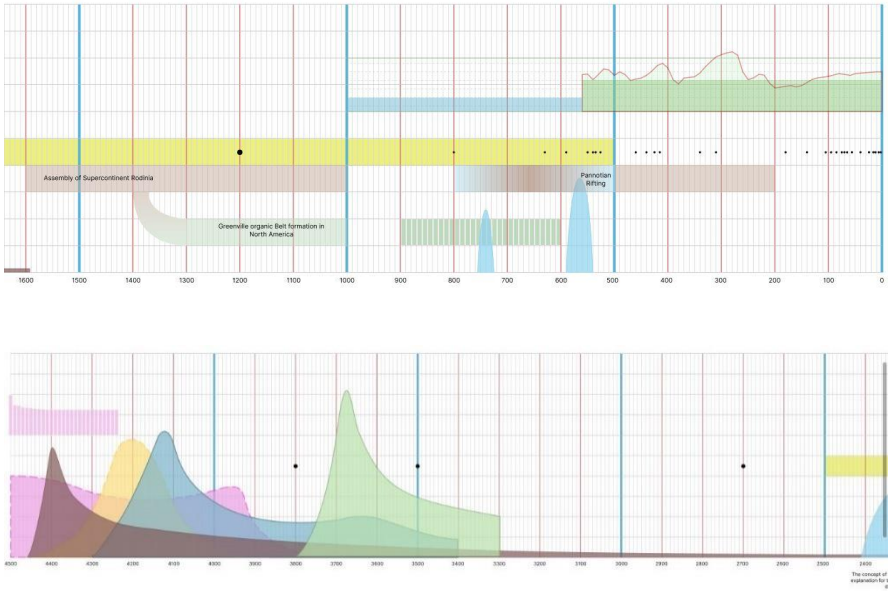


Figure 19a (up), 19b: Figures showing exploration of a Horizontal Timeline (compressed to fit into the page)

Figure 19a explored how Geological events could be represented via color coded bands. (Yellow- geologic events, green- plant evolution; brown- animal evolution). Further, the data points of Evolution of Life (i.e. formation of new taxonomic classes) are depicted by black dots. Initially, the dots varied in size, depending upon the prominence of that specie in time. However, this soon caused confusion and was removed after preliminary user testing.

Figure 19b shows the events marked by curves. The width of the curve indicates the duration of the event, and the maximum height represents the phase where that event was most prominent (it is also assumed to be its most accurate time). However, on addition of multiple such events and processes, the graph became overwhelming for the users to comprehend, and needed to be reduced to simpler form. It also became tedious for the users to scroll through the events presented in this manner.

Fossil vs Rocks

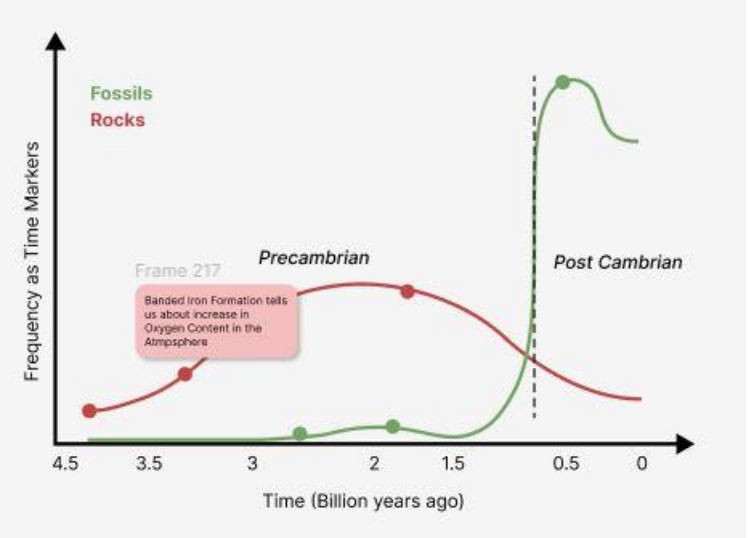


Figure 20: Visualization showing the comparison of Fossils and Rocks in gaining information

This visualization aims at making the users understand how Fossils and Rocks are used as geological time markers. It also serves as a

means to validate the information what would be presented further to the users. The presence of a Skeletal System near the beginning of Cambrian Period (542 mya) resulted in a boom of fossil records.

Visualizing the Effect of Fossil Records over Time

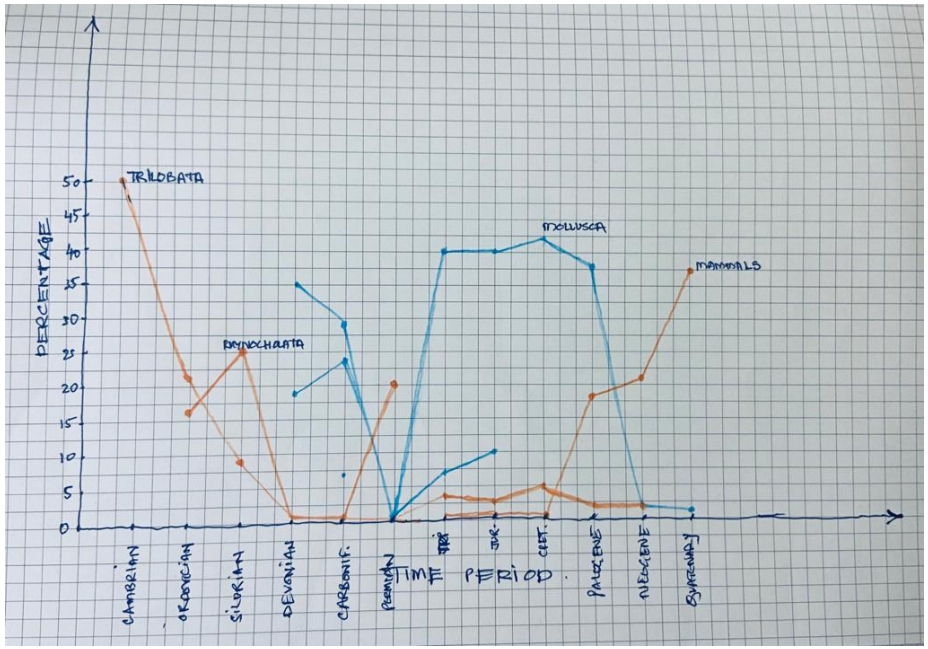


Figure 21: Initial Sketch of Fossil Records since 542 mya

This visualization helps in making users understand how fossil evidences are used to factor the dominant species of a time period. The rise in mammals, for example coincides with the decrease of Sauropsids and Dinosauria (Dinosaurs)

Circular/Radial Encoding of Data

One of the challenges of a linear encoding system was that it became too long for the users to visualize the entire data at a glance. This somehow was against the envisioned goal of the project, where the entire evolution could be depicted together. Hence, I explored Circular Timeline, where this information could be put together in a single interactive visualization.

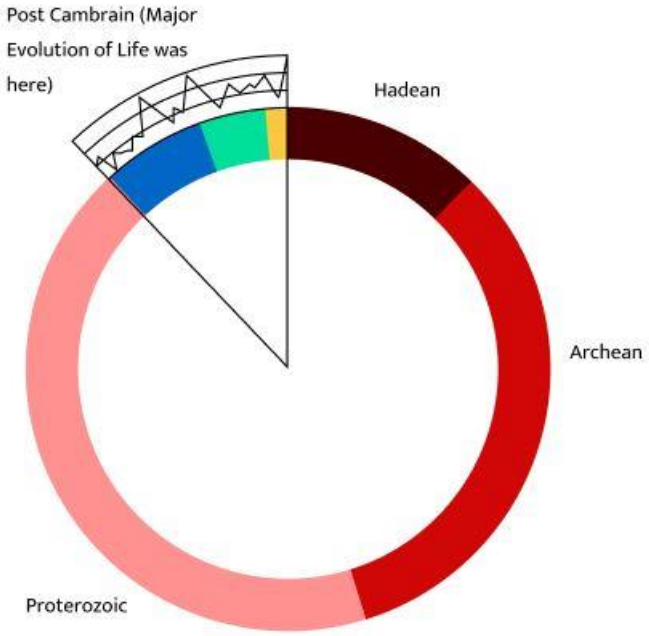


Figure 22: Representation of a Circular Timeline. Different colours show different periods of geologic time

Next type of visualization was more Data Driven in nature and followed a Circular Grid System, similar to Sun Burst diagrams. However, after making the initial entire timeline on a circle, the area left for the latter 542 mya (Post Cambrian Periods) was insignificant. As most of the encoding had to be done within this region, it was decided that the circular timeline would focus on the latter 542 mya, with a representation of the earlier 4 billion years for context.

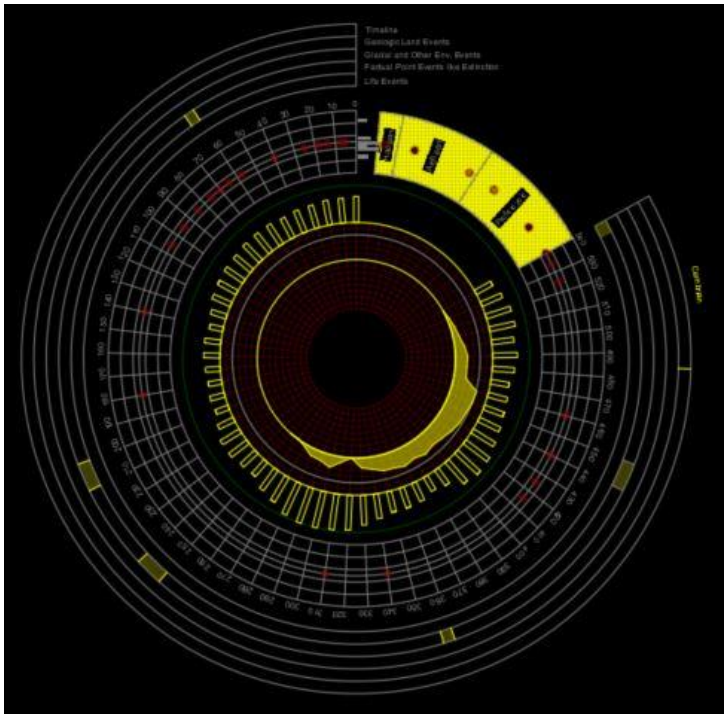


Figure 23: Reworking on the TimeLine. Hatched area depicts the rest of 4 billion years.

At this stage, a preliminary user testing was done to understand which form of encoding and visualization is most effective with the users. The impact of narrative was also studied, that helped me to redefine my entire structure (as described earlier)

Figure 24: Sea Level marked in blue (innermost Circle), and Oxygen marked in the form of Vertical Bars

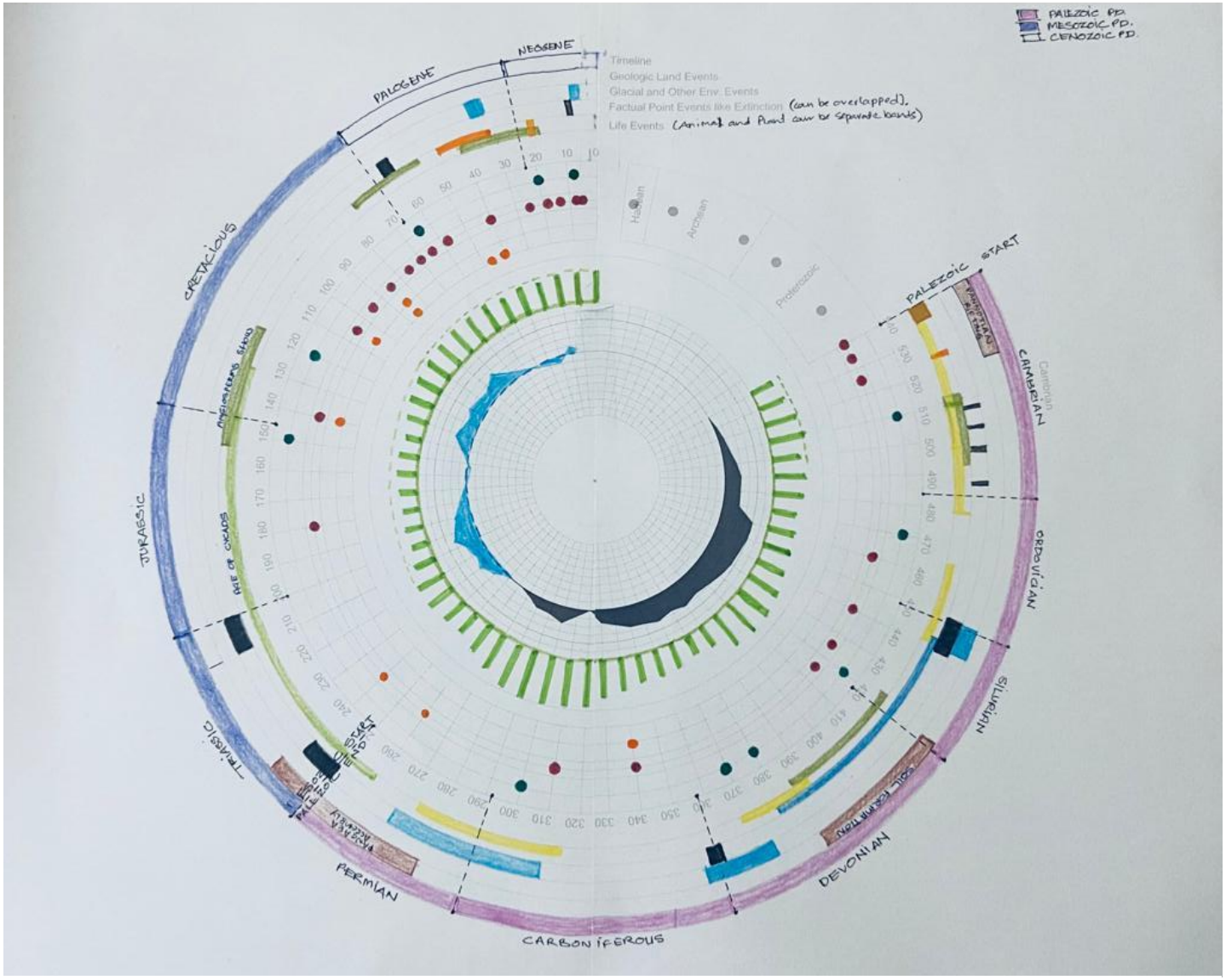


Figure 25: Visualization as used for Preliminary User Testing

Preliminary User Testing

The above ideations were shown to 8 different users (6 non-design background, 2 design backgrounds). All the users know the basics of Biology and Geography, since a basic understanding and interest in the subject is desired for the visualization to be comprehensible. I gave the users 10 minutes each to understand the concept and go through the visualizations individually. All the users were asked to go through the visualizations, but not in any particular order. (However, the circular visualization was shown at the end for each user) The following were the main observations:

Narrative:

- Users found narrative to be an important element to understand the visualizations in case of Idea Illustration. (Vertical Infographic)
- Some users felt that the narrative was becoming too long, and was taking more attention than the visualization. They suggested some parts of the narrative could be included in the visualization itself, while the narrative could focus only on the metaphor.
- Multiple curves overlayed on top of one-another caused confusion (Horizontal Visualization)
- The impact of 'Life' was substantially reduced in case of Horizontal visualization, since the initial timeline of 4 billion years was considered boring by some (less informative)
- Metaphor was not impactful until the end of the journey, where timeline started getting expressed in seconds, in comparison to the earlier mentioned years. (Dinosaurs lasted 13 months, as compared to 79 years of existence of Moon; or Human Line Separated from the Chimpanzees, just 7.5 hours ago!)

Visualizations:

- Vertical Visualizations were considered to be too long by some. Some of them lost the connection between species.
- Circular Visualization was found to be more complete, and more attractive by the users. The relationship between environment, materials and species' evolution was clearer. However, different representations (some radial, some linear) confused the users.
- Vertical Illustrative Timeline was better received than the vertical and horizontal encoded ones since it had more 'elements of surprise' and a connection with the users.
- Interactivity with Circular Encoding was desired. However, illustrative visualization was observed to be self-explanatory, since it ran along with the narrative.
- Users did not understand the importance of Geologic Time Periods. It would be better to make chapters on the basis of **Recognisable Events** instead.

A couple of users also remarked, 'This understanding is giving me existential crisis', hence proving that the sense of scale was being transferred to the people.

Final Design

Taking insights from the preliminary user testing and the feedback, I redefined the needs and structure of my narrative. I also removed some visualizations that held no significant importance to the story like the paleogeography maps.

Needs

- Make narrative crisp with a single Metaphor
- Make Chapters (Parts) of Narrative based on Recognisable Events and not based on Geologic Time
- Use Micro-Interactions for seamless connections
- Give interactivity to let users explore what they want to
- Limit the exploration to roughly 30 minutes, since the users cease to take interest after that time
- Convert all into Radial Visuals to maintain consistency

Encoding Strategies

Theme: Overall colour scheme was changed to a dark theme to resonate more with the topic. Size of the visuals were also increased from initial ideation (Fig 26- initial ideation). The chapter names were now visible only on hovering on the Boxes labelled from 1 to 8. (Fig 27)

Layout (Main Screen): In the revised layout, (Fig 27), the grid occupied a majority of the space. A scale was also added. Further, intervals were marked at every 1 billion years of time span.

Layout (Chapters): The layout (Fig 28, pg. 35) was designed in a manner that the users first read the narrative and then interact with the visualizations. Animatics occupy the centre of the Visualization to stay in context.

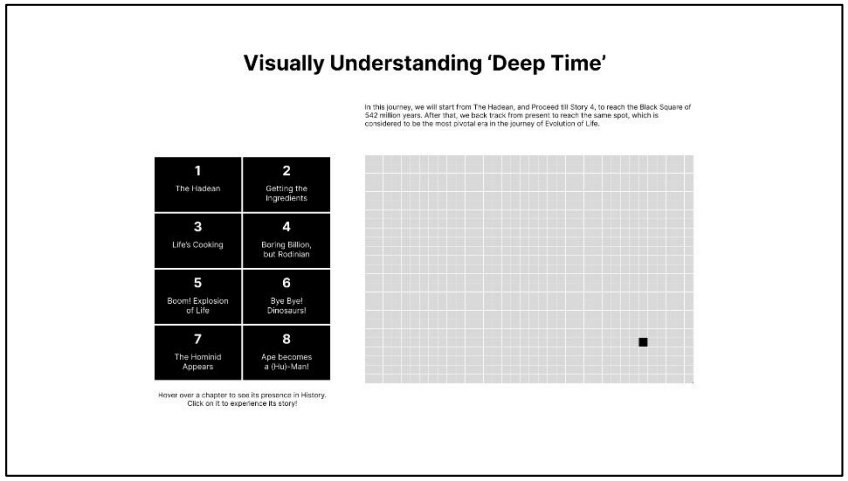


Figure 26: Initial Layout of Homepage using Light Theme

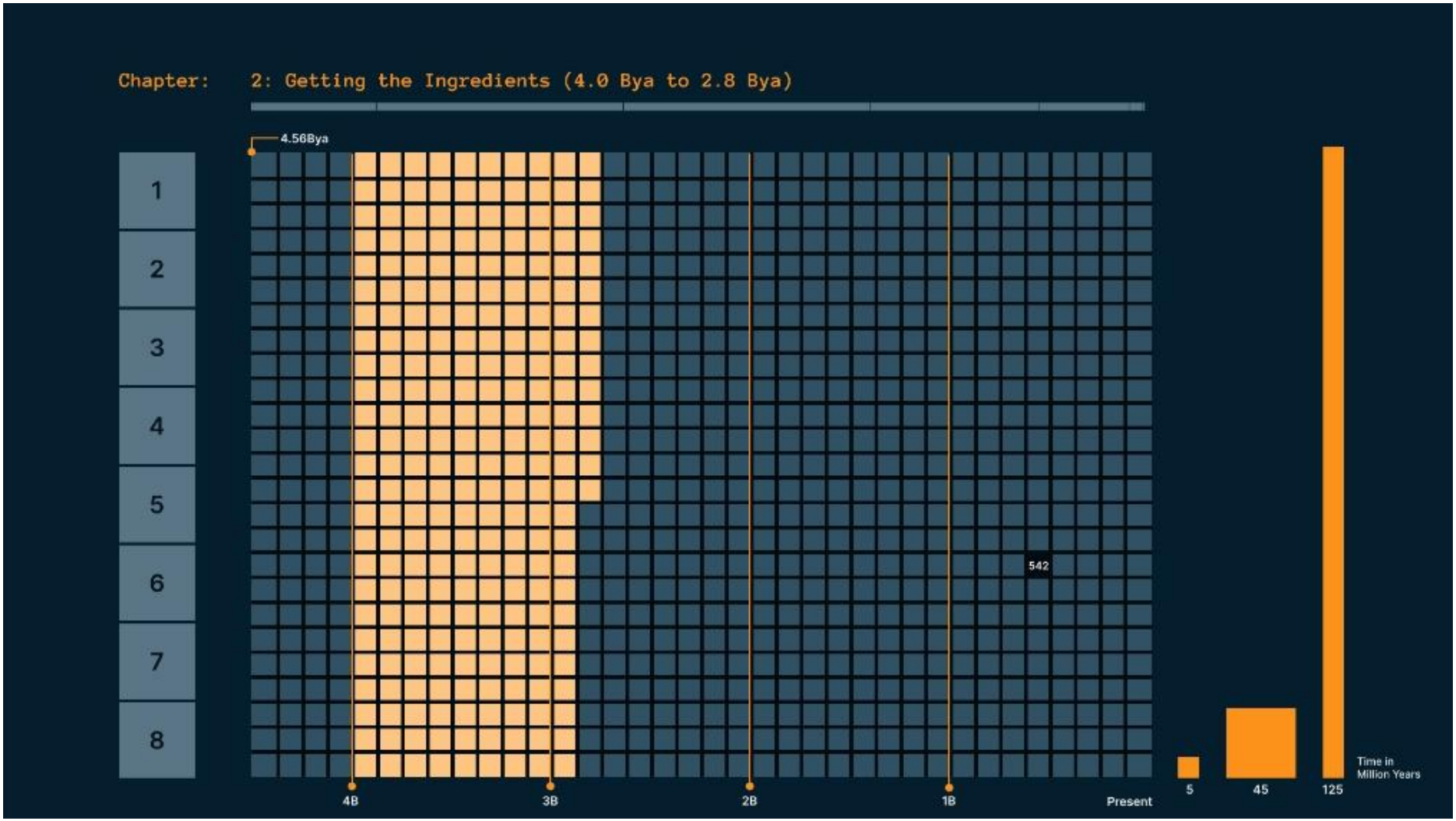


Figure 27: Revised Layout- Dark Theme, and larger visuals with the addition of scale. Intervals at 1 billion also marked

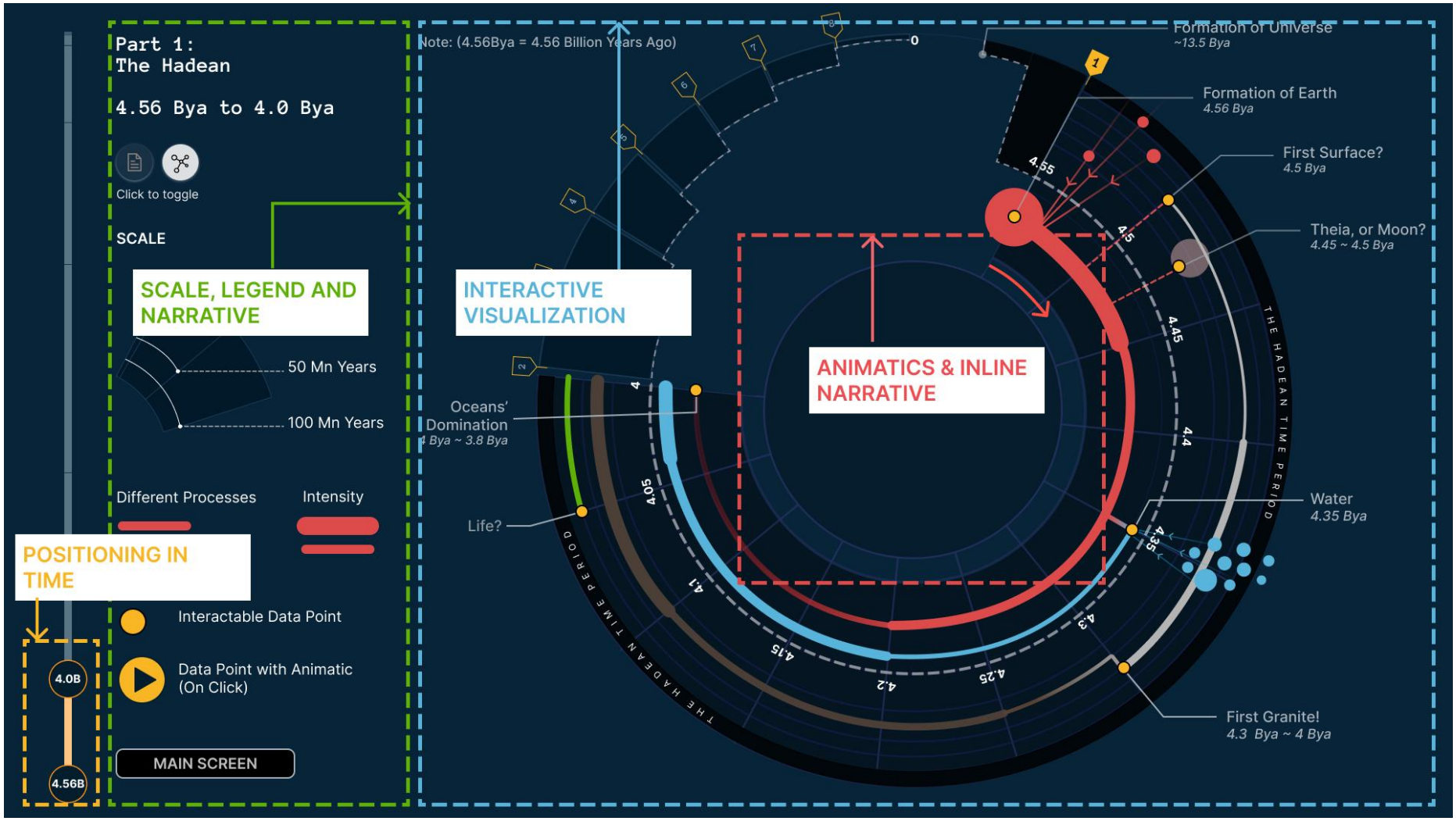


Figure 28: The Layout of Chapters Page

Timeline: Time was marked with a dotted line and a scale was given to it. This dotted line continues throughout, from the past and goes till present time, to maintain continuity. The text of 'Time Stamp' was also increased in size. A scale was also added.

It was ensured that the Timeline never 'Joins' with itself (Fig 28), otherwise it would be a misrepresentation that the time ended. In the figure below, time is marked in Yellow. The bends represent the different chapters. Semantically, the past is of a darker tone than the current chapter, and the future is of a lighter tone.

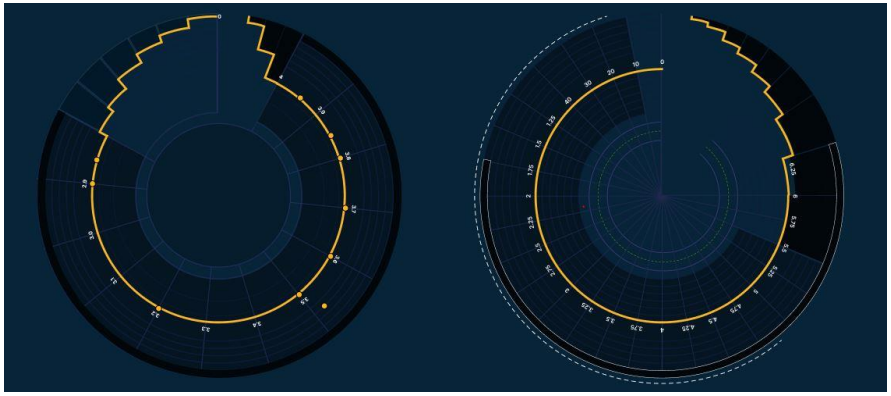


Figure 28: Timelines marked in Yellow. (Left- Chapter 2; Right- Chapter 8)

Scale in Visualisations: All intervals on radial lines belong to the same time (Fig 29). It is the radian that defines the progression in time. In Fig.30, Yellow dots are on the same time. Green is past, and Red Dots is future. Events on the same radial line lie in the same time. This helped in visualising the corelations and cause-and-effect relationship between different geologic events.

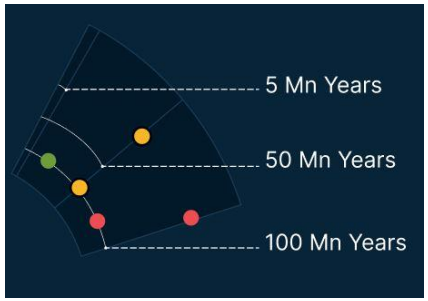


Figure 29: The Radial Time Scale

Colour, Lines, Thicknesses: Although the colours do not represent any particular kind of data, they were chosen in such a way that they semantically match with the type of data they represent. Example- water related events were marked in blue, while the land related events were marked in beige/brown. Their thicknesses, however, show how prominent that event was in that period.

Figure 30: Defining Processes and their thicknesses. They do not have a scale, they are just representative throughout

Defining Hover & Click Interactions: Hover and Click based interactions were defined and maintained throughout the project.

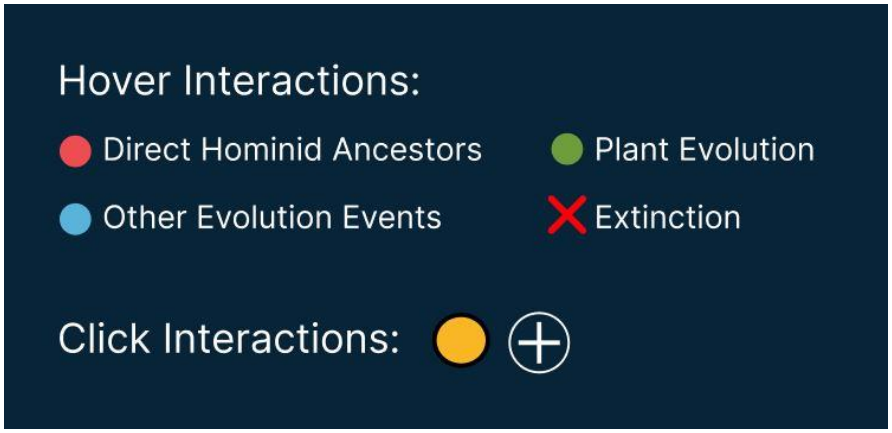


Figure 31: Colour Coding was done for Click based and Hover based interactions. These were also defined in the legend.

Use of Animatics:

To support the narrative, I created small animations that helped users visually see what happened during those time periods. These were found to be more important in the initial phases of Time, where contrasting and sudden changes on the planet were observed. These also supported some parts of narratives that were heavily scientific in nature, like the formation of Banded Irons and its relevance on Oxygen Formation.

One such animatic can be seen in the figure below (Fig 32). This played at the centre of the visualisation, so that a connection between the graphic and text could be made.

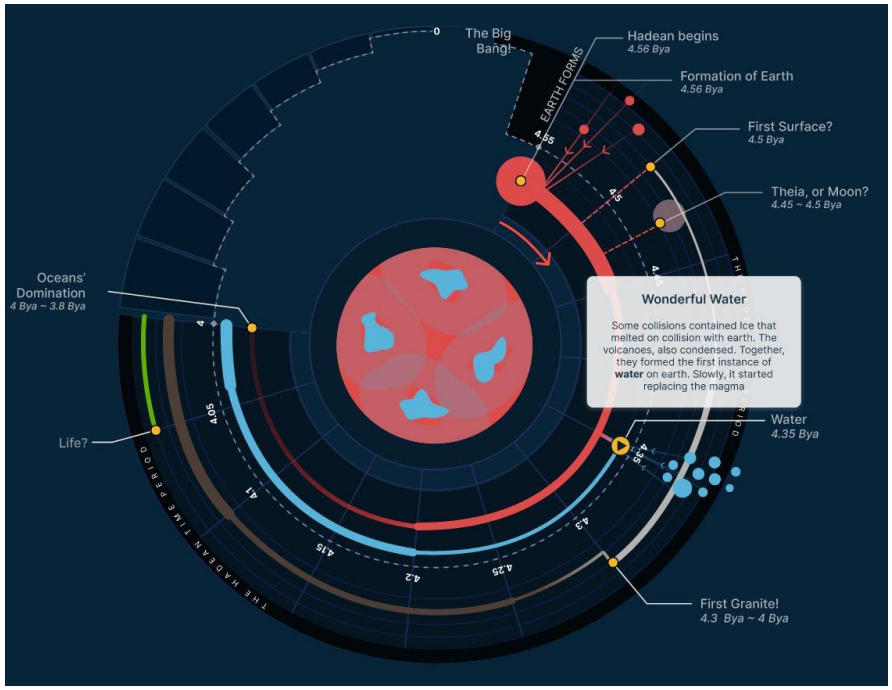


Figure 32: Animations (Static and Dynamic) Playing at the centre of the Visualization. They are connected with the narrative in the overlay.

Book marks for switching between chapters: Every interactive visualisation had a series of Book Marks labelled from (1-8) to navigate from one chapter to another without returning to the main screen. These had 3 states- static, hover and current chapter. (Fig.33)

Figure 33: Bookmarks with its 3 states

Designing Micro-Interactions:

Some micro interactions were implemented throughout. These act as linkage between chapters, and also as visual cues for the users to interact with.

Animatics: On hovering any interactive node, if it contains an animatic, a 'Play' icon is shown. For the non-animatic ones, the interactive node simply becomes larger in size.

Figure 34: Micro interaction showing how the Data Nodes change on hovering onto them.

Delay showing interactive features: While moving to a chapter from the home-page, a few of the interactive nodes become large and their text is displayed for 2 seconds (Fig. 35). This delay acts as a prompt to the users that some elements are interactable, while the others are not.

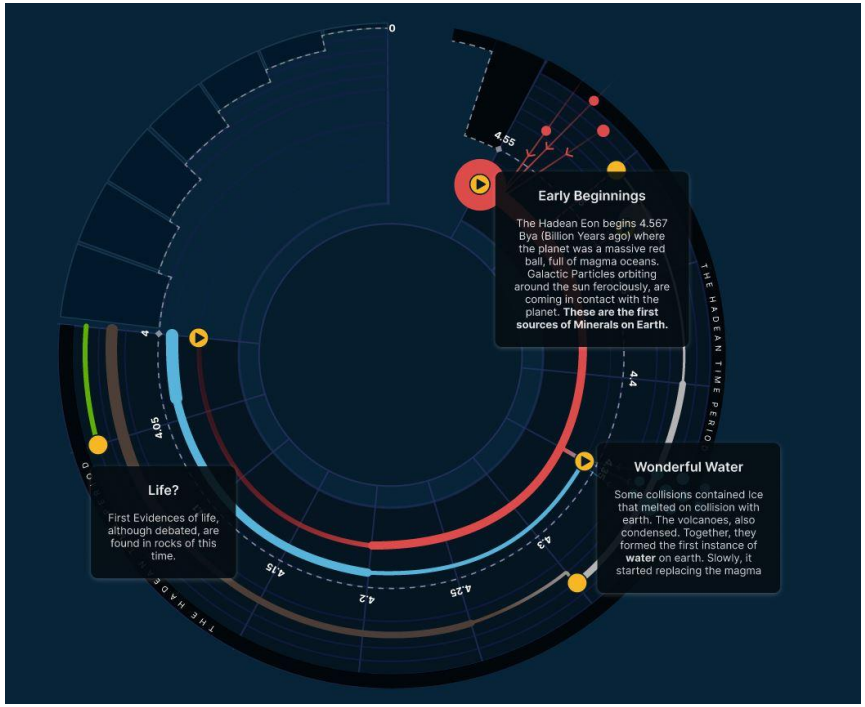


Figure 35: Delayed Micro interaction that opens up a few of the overlays on the Visualization

Toggle Switch: There is an option to toggle between the Narrative and the Data Reading Instructions.

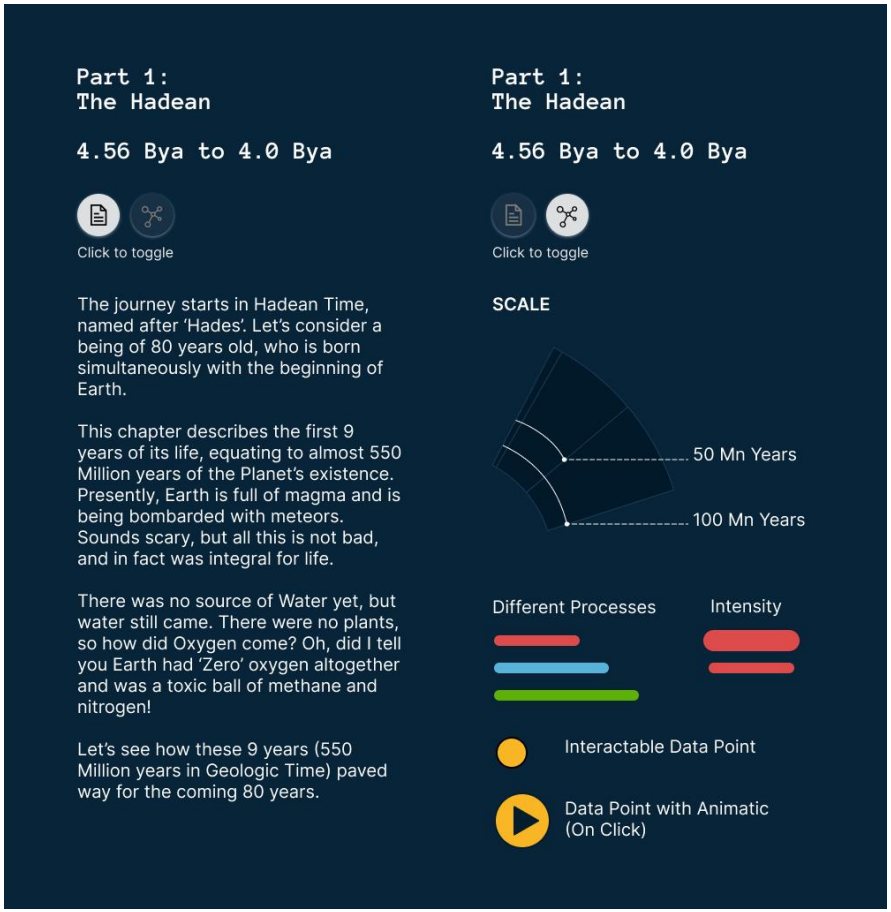


Figure 36: Toggle between Narrative and the Reading Instructions for the visualization

Transition: On transitioning from the Homepage to the Chapters, the area gradually fills up in a scaled linear bar, that is carried on to the next page. This bar highlights the positioning of the chapter in the Geologic Time.

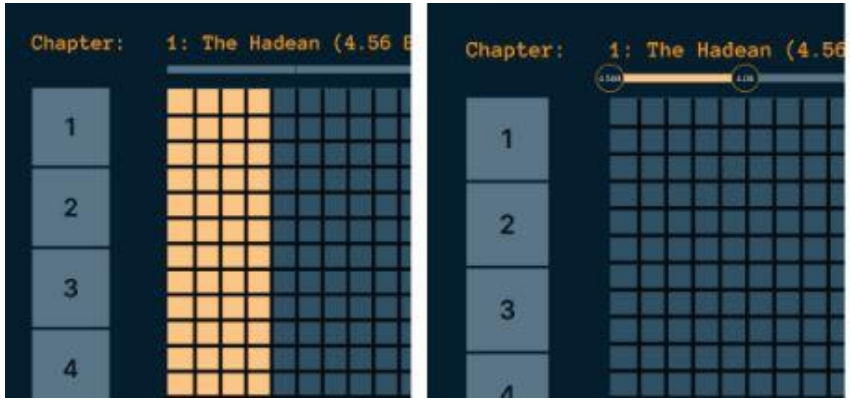


Figure 37: Filling up of Area into the Linear Bar

Figure 38: The Linear Bar moving from Home Screen (Left) to the Chapters (right)

Buttons: Buttons are used to show/ hide certain layers of encoding. Some of them included Text, Legend, Narrative, Zoom and Returning to the main screen. These were especially useful in the chapter that contained different layers of encoding.

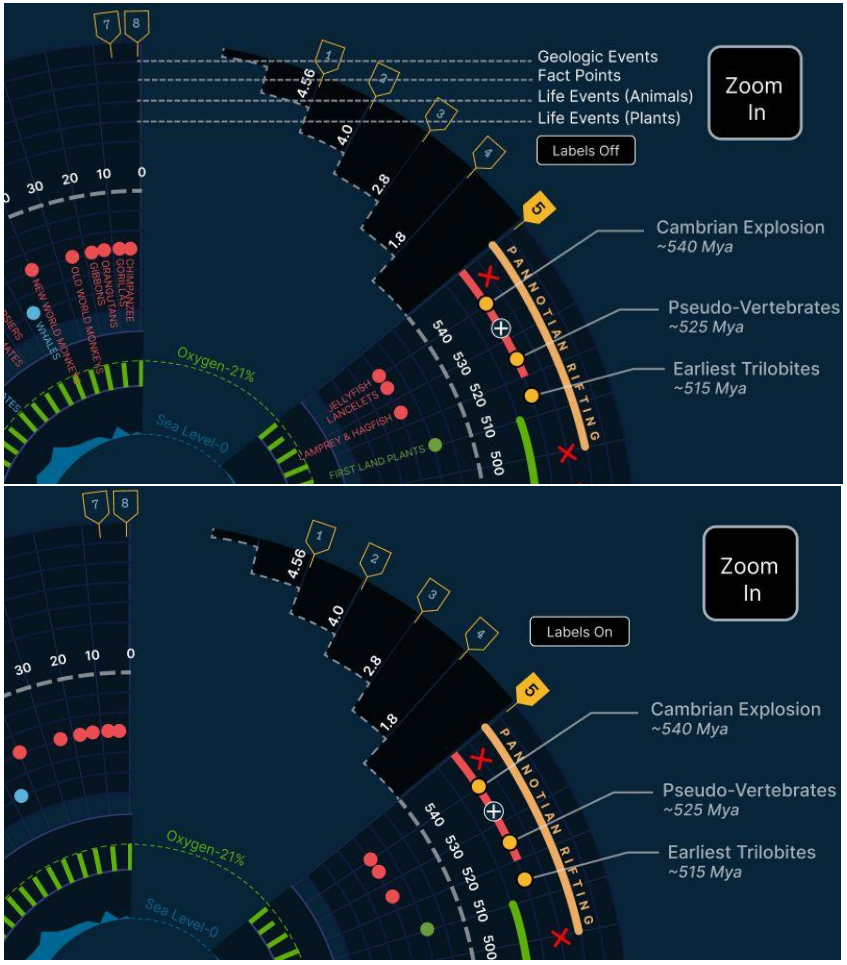


Figure 39: Use of Buttons of Label and Legend. (Top- On; Bottom-Off)

Hover: The text can be enlarged in certain areas on hovering onto its respective Data Node.

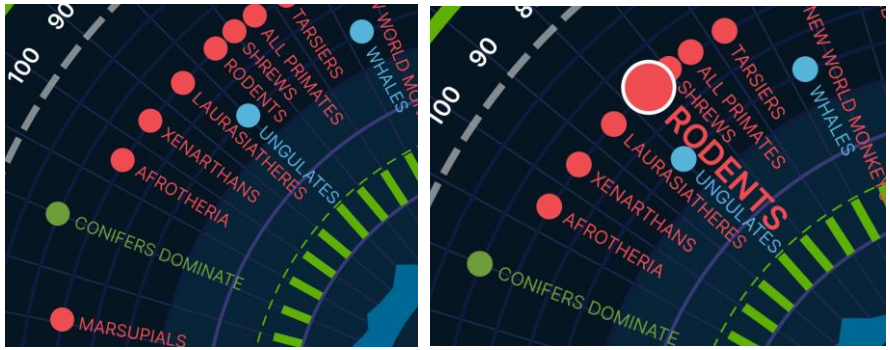


Figure 40: Hovering to enlarge some aspects of Text

(This space is intentionally left blank)

Prototype & Final Visualizations

Introducing Deep Time

This phase introduces the Users to the concept of Deep Time and how it is measured. The information about measuring time also helps in making the users assured that they will go through a reliable set of data. The users are also introduced to Atom, the imaginary protagonist of the Narrative.

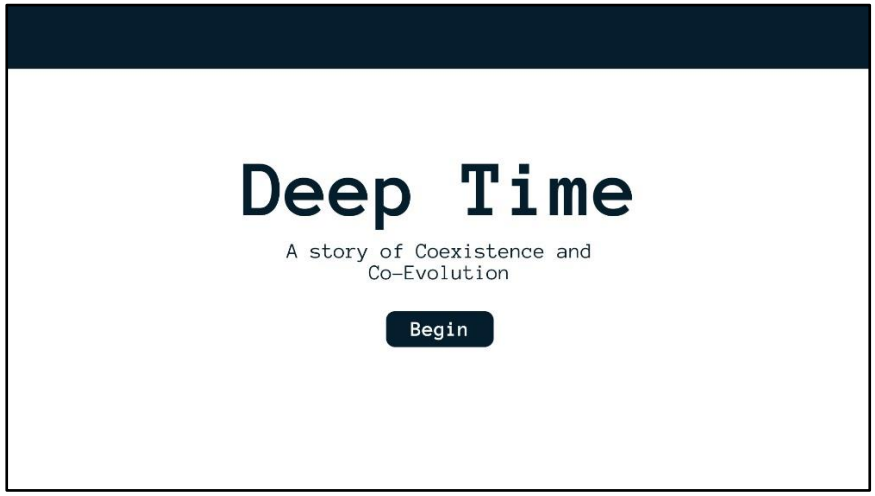


Figure 41: The opening page, introducing the title

An Archimedean Spiral (Fig-42) is used to show a snapshot of Deep Time, with the past being narrower due to lack of recorded events.

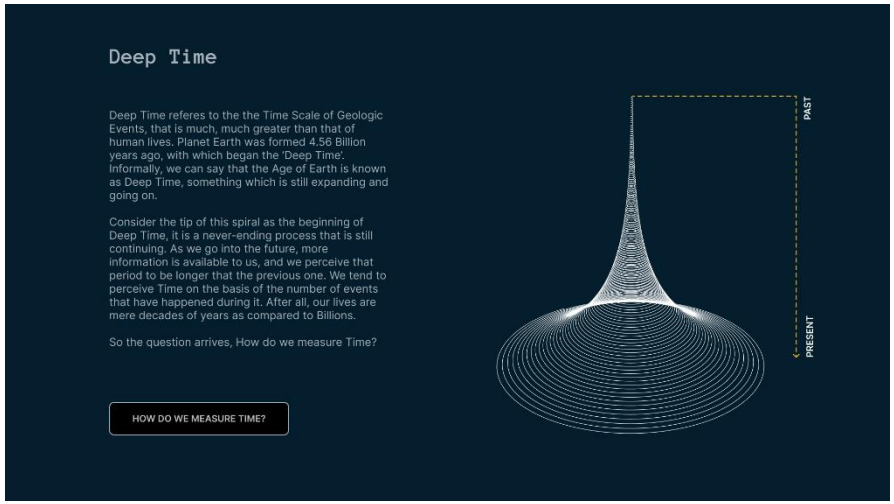


Figure 42: Using an Archimedean Helix to show a Snapshot of Deep Time

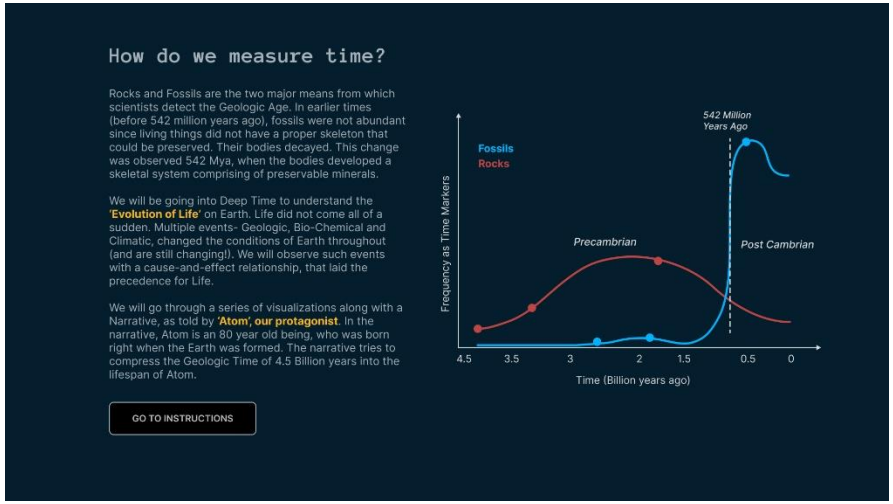


Figure 43: How do we measure Time?

Instructions for the Users

The users are advised to hover through all the chapters to see their period in Geologic Time. However, as part of the narrative, they are requested to begin from Chapter 1.

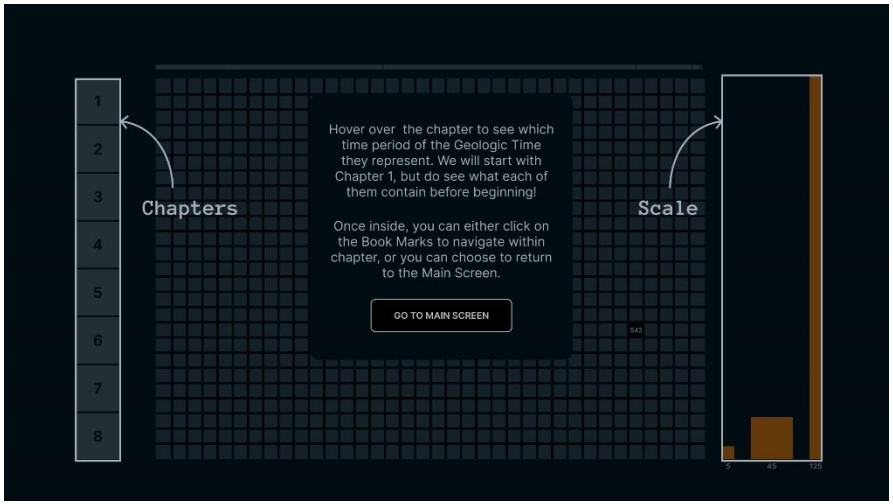


Figure 44: Instructions Page

Main Screen

The Main Screen shows a 36 x 25 grid, with each box representing 5 million years, for a total of 4500 million years. It has 8 chapters which hold equal importance in the Geologic Time.

Hovering on any chapter highlights the number of squares equivalent to its time period (Fig 45). The title of the chapter is also displayed. One drawback is that the users cannot see the title of all chapters at the same instant, and have to hover through all. However, this was done so that they can visualize how different scales of time (from billion years to mere thousands) can hold equal importance, highlighting that the changes are much more rapid as they were earlier.

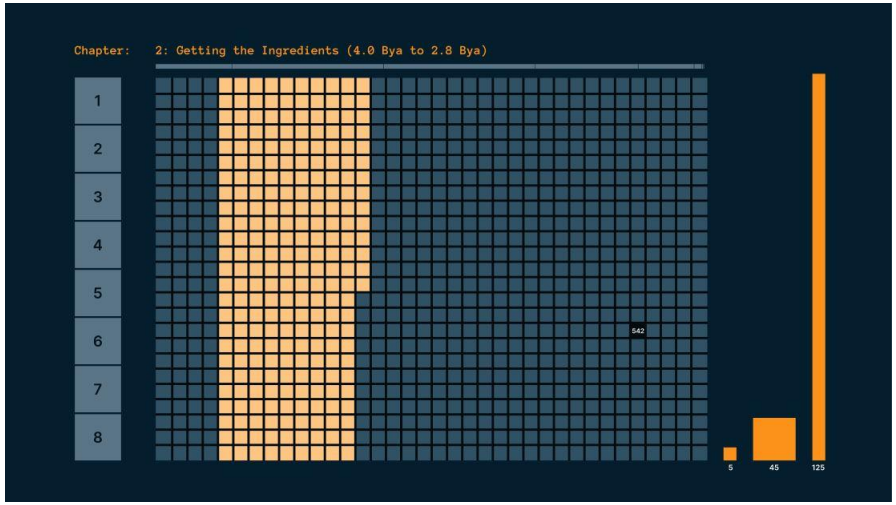


Figure 45: Hovering on a Chapter on Homepage

Chapter Screens and Visualizations

The first chapter (Fig 46, page 43), called 'The Hadean' introduces Atom and the first 500 million years of Earth's existence. The first Exploratory Data Visualization is now presented. The dashed line represents the Timeline, with it being thicker in the period defined by the visualization (560 million Years). It starts from 13.5Bya and goes till 0 (Present time). The other chapter are marked by

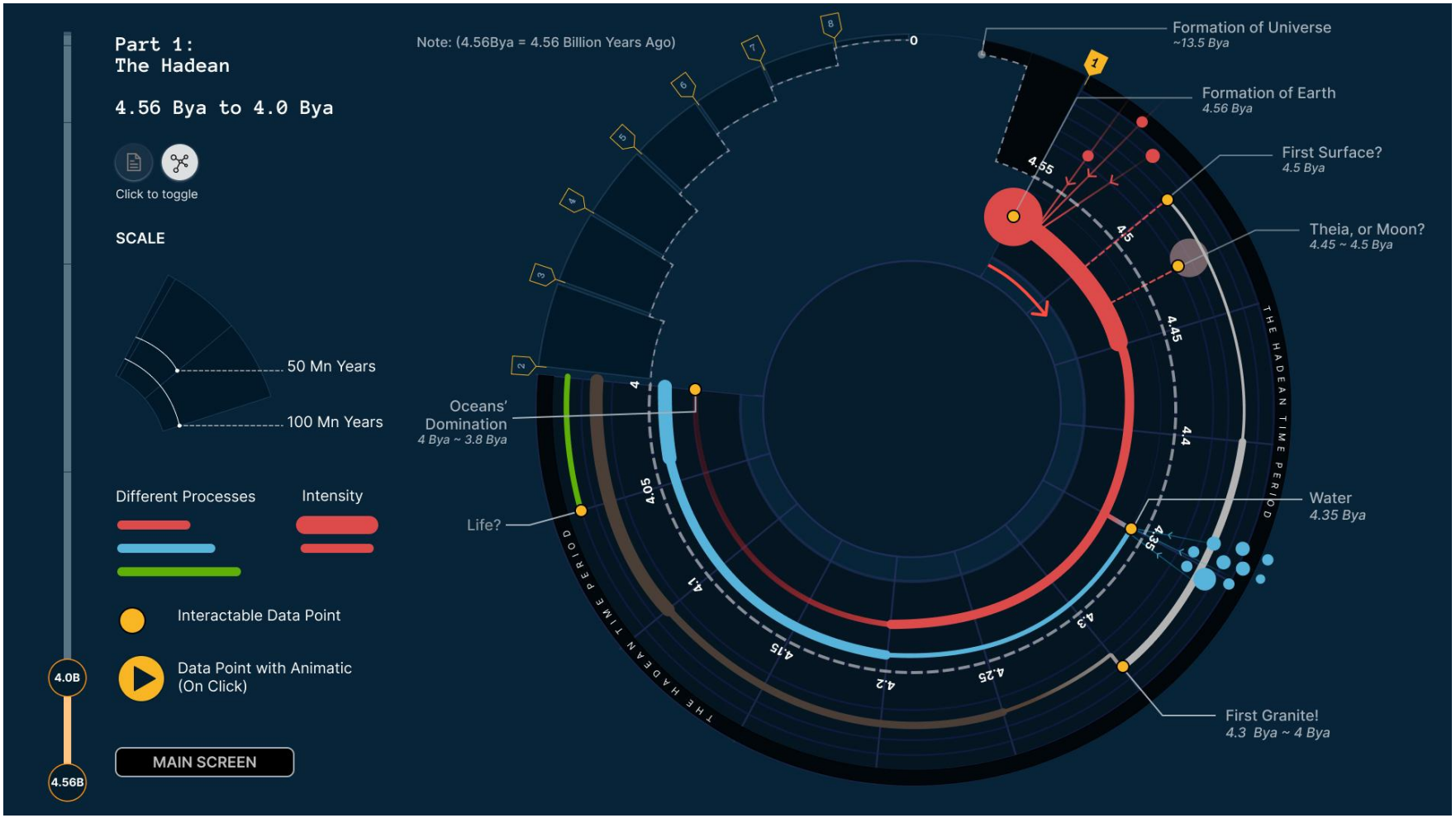


Figure 46: Chapter 1 showing the Exploratory Interactive Visualization along with the Legend

Bookmarks having numbers (2-8) written on them. However, for the first time, the users are asked to go through the chapters progressively. The layout also contains a vertical time-line, that represents the period this visualization represents in the Geologic Time. Similarly, each of the chapters contain an interactive visualization. The details of which differ. They are fairly constant in

the first four chapters, after which the amount of Data Points substantially increases. This happens when there is an explosion of life, termed as the Cambrian Explosion. The users now realise the significance of the number 542 in the home page. Cambrian Explosion happened due to various reasons, linked to one another. Some of them being a high level of oxygen in the air (matching current levels), bodies developing a skeletal system that helped preserve their records and protected them against the harsh climate etc.

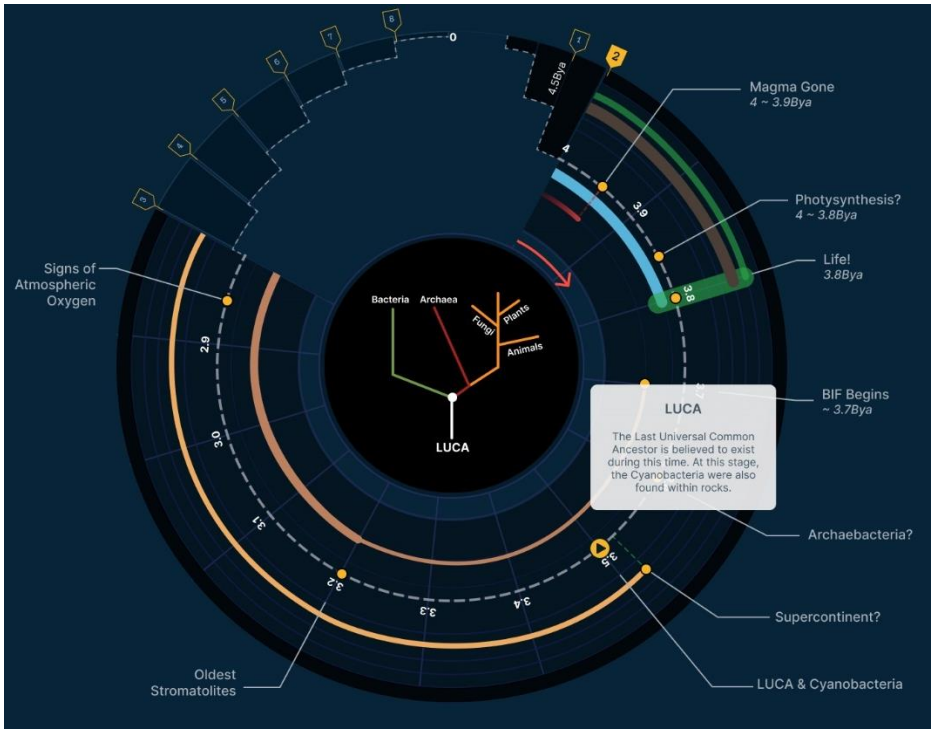


Figure 47: Interactive Visualization for Chapter 2, with LUCA Data Node Selected

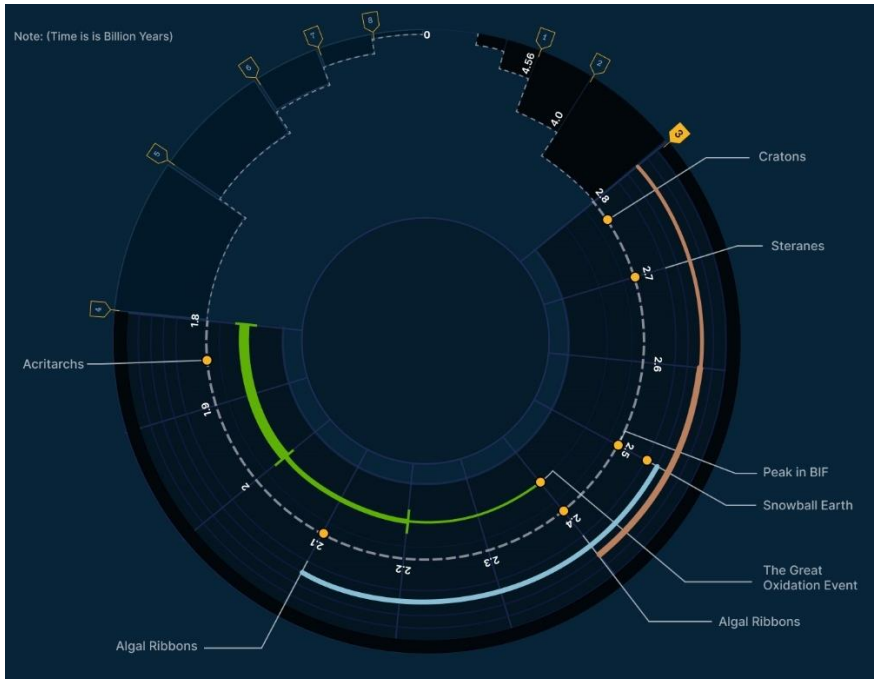


Figure 48: Interactive Visualization for Chapter 3

Chapters 2 and 3 cover the next 2 billion years. Here, one radial unit corresponds to 100 million years, as shown in the legend. The number of interactive data points also are lesser in comparison, since these were times for which recorded evidences are not much. However, a few critical stages, such as the earliest forms of life and some drastic atmospheric changes were represented.

In Chapter 4, the scale of events changes for the first time. For the first 80% of the time, we observe Chapter 4 follows roughly the same encodings and time scale as that of the previous events. In fact, this

was the phase when Earth was in its most stable environment. However, the final 300 years saw one of the most dramatic phases in Earth's life, that resulted in an evolutionary burst.

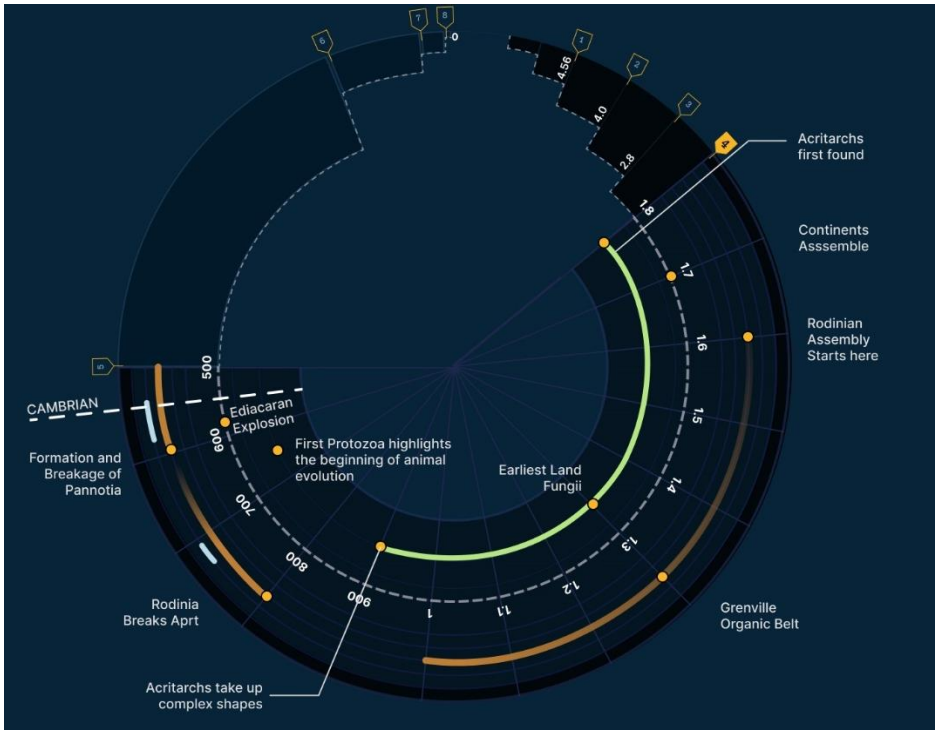


Figure 49: Interactive Visualization for Chapter 4

Chapter 5 sees the first dramatic change in the visualization. The number of Interactions drastically increase. Thus, the number of interactive features (containing layers of data) increase. Here, Hover, Click, Hide, Zoom, and Swipe features on interactivity are explored. This is also the phase where Life actually emerges in the form of the five great kingdoms of life. The following layers of data are encoded in the interactivity:

- Name and Labels can be switched on/ off using a button. Further, while the names are on, hovering on the Data Node makes the Name Larger.

- There is an option to hide/ show the legend The Legend represents which circular line contains what type of information.

- Hover-Based interactions are mostly included in the inner circle. These are red, green and blue circles. These represent the hominid radiation from early animals, plants diversion, and evolution of other species (that do not directly affect the hominid family) respectively.

- Click Based interactions are confined to 'plus marks' and the yellow circles (which have been clickable throughout the project to maintain consistency). These data points have also been labelled, so that the users can decide which out of these they want to explore in-depth.

- The 'plus marks' opens a translucent sector that defines certain critical periods in this entire time scale like the Age of Amphibians, Age of Dinosaurs etc.

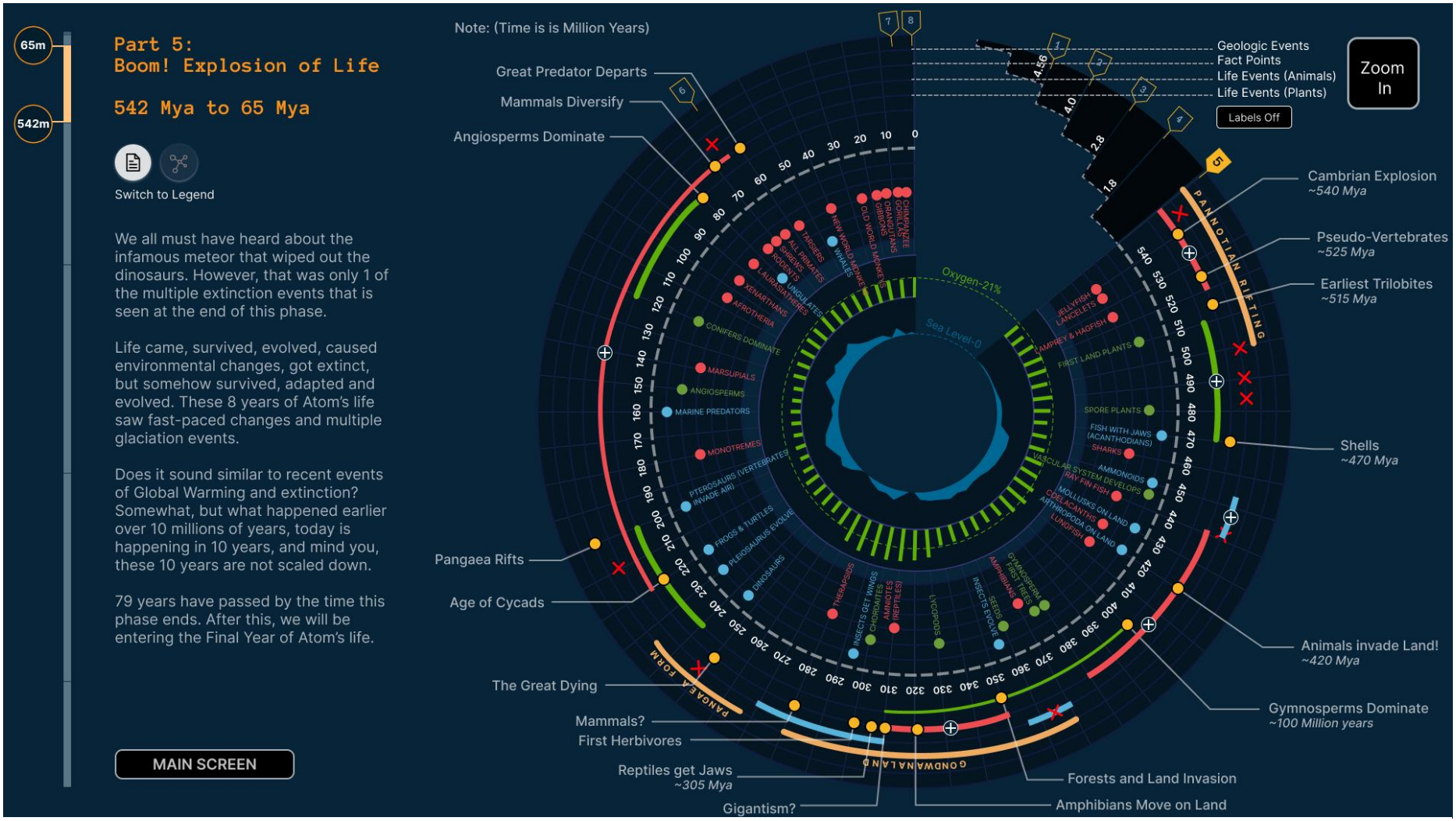


Figure 50: Interactive Visualization of chapter 5

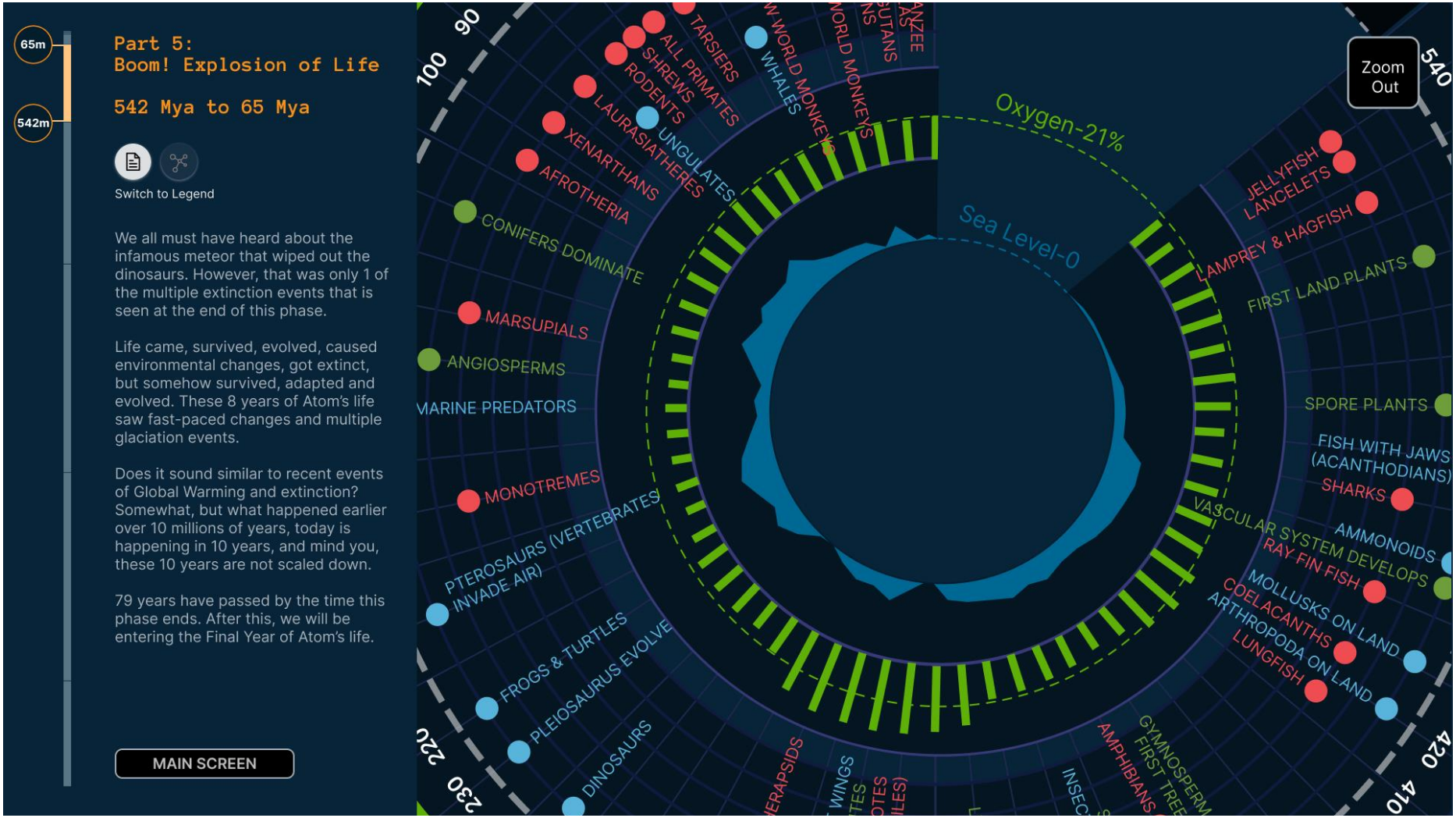


Figure 51: Zoomed in View of Chapter 5 Visualization

Chapters 6 covers a detailed explanation of the last 65 million years, right after the extinction of the dinosaurs. We finally enter that period of time that might be relatable to the audience. The visualizations here, although do not have such extensive data points, they contain more minute details. This is also an attempt to highlight how smaller periods in a Larger Time scale can be detailed out. In this, we are largely focused on placental mammals and their relation with the Geologic Entities.

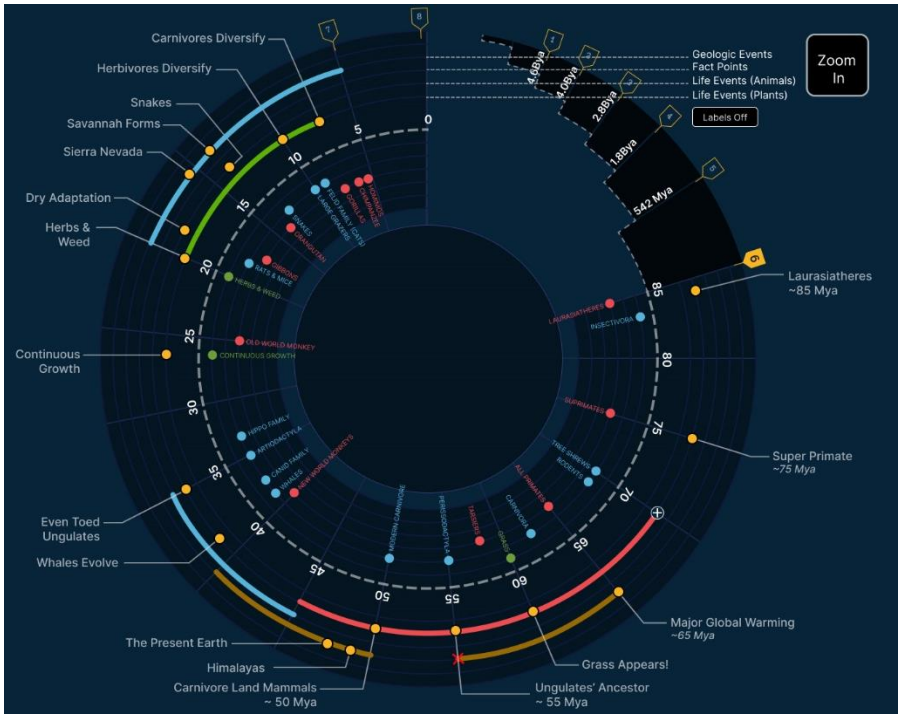


Figure 52: Chapter 6 showing the detailed evolution of Mammals

Chapters 7 covers the detailed evolution of one of the families of mammals- the hominids. This is the family from while the Homo Genus evolved. This is also an attempt to show hoe the larger data set can be linked to timelines of individual species. Hence, the hominid family is studied in larger details, with the evolutionary features, and their geographical migration being represented. The hover and click interactions are kept consistent.

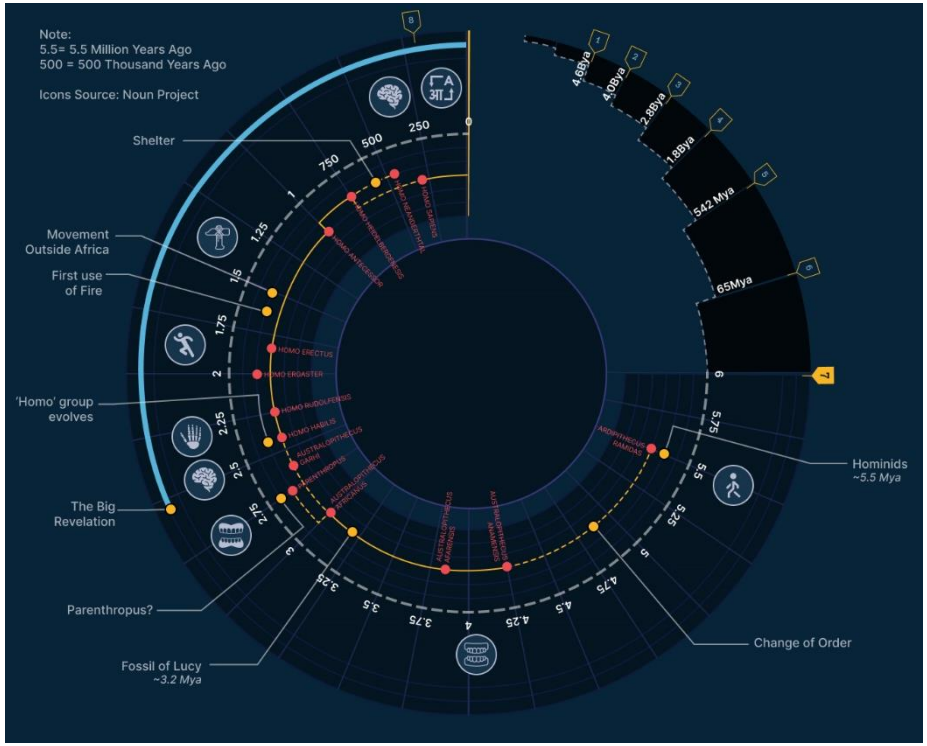


Figure 53: Chapter 7 showing details of the hominid family. The major evolutionary features are marked using symbolic images

The last 2 chapters are an attempt to highlight how certain details can be explored in a larger data set with the use of Selective Zooming, with the Context and Details being shared simultaneously.

Chapters 8 being the concluding chapter highlights the most recent development (in the last 200,000 years). This is also the chapter where the metaphoric time is conveyed to the users as they are able to gauge the overall Geologic Time with the time, they are aware of. The project ends with a small bit of conclusion that reflects how the Geologic process are inter-related with one another, and the fact that the changes are now rapidly taking place.

Evaluation Plan

1. I would start by engaging the users into a brief discussion about their interest in Geology and Evolution of Life. It would serve as an ice-breaker to gauge their interest in the subject. Will include an introduction of the project.

2. I would ask the users to Think Aloud while going through the prototype, which would enable me to identify the pain points and strengths of the project. Note making for the same would be done. I would also note their interactions with the data points to see if any pattern is observed. We might be able to find the user behaviour in interactive data visualization through this means.

3. The users would be asked about the overall learnings, and whether the project generated further interest in some topics.

Qualitative Evaluation

The feedback and user responses would be a part of the Qualitative assessment. The pain points would be noted down. Further, Expert Validation and engagement would be also be a part of it.

- How effective were the Visualizations to help in understanding the concept of Deep Time?
- Did the Story Narrative help in understanding the flow of time, and understand its scale.
- Would you look into some of the concepts after this evaluation? If yes, what would they be.
- Did the visualizations change your perspective about evolution of Life.
- Were you able to understand the Cause-and-Effect relationship that was portrayed in the visualizations.

The Success metric would vary among different entities as follows:

Narrative: The narrative is supposed to be an extension to the visualization. It should not overpower it. Although the Visualization needs to be self-sufficient, the importance of the narrative is to

concise entire Deep Time (4.5 billion) into a span of 80 years, thereby enabling the users to understand the scale of time.

Success Metrics:

- It should not be overwhelming.
- It should make the scale of time clear to the users.

Final Visualization: Thinking aloud would give an insight into the experience the users went through while understanding the visualizations. It is important to gauge the interest the user shows while going through the main visualization. For the interactive data, whether the user is intrigued enough to go through every interaction would be noted.

Eventually, they would be asked to summarise their experience and be asked to give the Likert Ratings as mentioned above.

Quantitative Evaluation

Evaluation would be done in order to find how users interact with 'interactable data points' (I will be noting observations for only click-based interactions, and not hover). A list of all interactable elements have been combined and tally marks would be every time a user interacts with it.

Further, time spent on each of the chapters. This would help understand if there is a pattern regarding the number of clickable elements an interactive Data Visualization should contain.

The following template was used:

USABILITY EVALUATION										
User	**Notes**									
USER - 1										
Interactions										
	CHAPTER 1									
	USER 1	USER 2	USER 3	USER 4	USER 5	USER 6	USER 7	USER 8	USER 9	USER 10
Toggle- data										
Toggle- Text										
Main Screen										
Formation of Earth										
First Surface?										
Theia, or Moon?										
Water										
First Granite!										
Life?										
Oceans Dominate										
Bookmark-2										
Bookmark-3										
Bookmark-4										
Bookmark-5										
Bookmark-6										
Bookmark-7										
Bookmark-8										
TOTAL TIME										
	CHAPTER 2									
	USER 1	USER 2	USER 3	USER 4	USER 5	USER 6	USER 7	USER 8	USER 9	USER 10
Toggle- data										
Toggle- Text										
Main Screen										
Magma Gone										
Photosynthesis?										
Theia, or Moon?										
Life!										
Archaebacteria										
Supercontinent?										
LUCA & Cyanobacteria										
Oldest Stromatolite										
Atmospheric Oxygen										
Bookmark-1										

Figure 54: Template for Quantitative Evaluation

Evaluation Results

Expert Review

I showed the final prototype to Prof. Sudipta Dasgupta (Dept of Earth Science, IIT Bombay).

I had previously also taken his advice regarding structuring of the chapters. The overall timeline was validated and the structuring of the chapters on the basis of Events, and not Time was praised. However, the expert also felt that the number of chapters could be reduced from 8 to 6. The experts also felt that the visualization focused a bit too much on the 'Hominids' and some concepts like Global Warming and its relevance could be highlighted more.

Taking cues from the evaluation, I included some additional data notes that contained information on climatic changes, and tried to relate the current climate change with that of the past, through the metaphoric scale. However, the focus was kept on the Hominids owing to the scoping of the project.

Qualitative Feedback

The prototype was shown to 9 users. They were asked to think aloud while interacting with the product. Further, a feedback session for 10 minutes was conducted to gauge their overall experience. The following were the main points of observation:

- 7/9 users stated that they could understand the scale of time
- All the users could understand the Predator-Prey relationship and the early evolution of life
- Chapter Connections were smooth and understandable
- Relatable Content and Terms like Homo-Sapiens, Whales, Chimpanzee, and even Pangaea were more inviting, hence saw more clicks and interactions
- 6/9 Users found Chapter 5 very overwhelming, resulting in them skipping latter portions of it. This was against the behaviour that I was expecting. The average time on this chapter was about 9 mins, though I was expecting users to spend around 15 minutes here.
- Users were attracted by Catchy Titles and Exclamations- '?', '!', 'Snowball', 'Great Predator', 'Demise'. This also shows that Captions affect how users interact with a data node.
- After spending certain time, users started to read the text and decide which buttons to interact with
- After switching between chapters, it was not intuitive to read the narrative due to Eye Movement being fixed on the Visuals. Hence, it might be better to include the Narrative within the Visualization itself, rather than keeping it on a separate overlay.

Quantitative Analysis

For the Quantitative Analysis, I recorded the number of times a user interacted with Data Nodes. The environment was semi controlled initially, and the users were told how to interact with the Data Nodes. They were also told about the 'Starting Point' of reading the visualization. Further, they were instructed to read the narrative before going through the visualizations. However, they were given full freedom to explore the visualization the way they wanted to and in the order of their choice.

The following things were noted:

- Number of times a user 'Clicks' on an interactive node and identifying Patterns (if any)
- Total Time taken per visualization (chapter)

For the evaluation, the nodes were defined as follows:

- Toggle (Switch Type)
- Zoom
- Text Overlay (Opens a text overlay on click)
- Text Overlay with Graphic (Opens an animatic)
- Clickable Icon (These nodes had a Symbol on them)
- Hidden Layer (Add Features on Viz)
- Navigation (Move b/w chapters)
- Return (Access the Main Screen)

The following results were obtained:

Total Time-Average time taken was 32 min 17 s (Highest- 36m 13s; Lowest 24m 29s)

Interaction with Nodes

'Text Overlay with Graphic' Nodes were interacted more than once more frequently

Formation of Earth	1	1	2	1	1	2	1	2	1	Text Overlay with Graphic
Theia, or Moon?	1	2	2	2	1	2	2	1	2	Text Overlay with Graphic
Water	2	1	2	1	1	1	1	1	1	Text Overlay with Graphic
Oceans Dominate	2	1	1	2	1	1	1	1	1	Text Overlay with Graphic
BIF Begins	1	1	1	2	1	1	2	2	1	Text Overlay with Graphic
LUCA & Cyanobacteria	2	1	2	2	1	1	2	1	1	Text Overlay with Graphic

Table 1: Table showing user interactions with the node- Text Overlay with Graphic

Captions and Labels

Nodes that might be self-explanatory were ignored (3 or less clicks) by Users. These mainly included 'Names of Organisms', 'Commonly known Processes' etc

First Granite!	1						1			Text Overlay
Fungi	1	1			1					Text Overlay
Rodinia Breaks Apart					1	1				Text Overlay
Reptiles get Jaws		1			1	1				Text Overlay
Angiosperms Dominate						1	1		1	Text Overlay
Major Global Warming		2	1				1	1		Text Overlay
The Present Earth		1	1		1					Text Overlay
Himalayas						1		1		Text Overlay

Table 2: Table showing Nodes with 3 or fewer interactions

Ambiguous terms saw equal clicks (4/9) or (5/9) -Users either ignored these or were curious to know more about them

Photosynthesis?	1				1	1		1	1	Text Overlay
Algal Ribbons	1	1			1		1	1	1	Text Overlay
Acritarchs		1	1		1		1		1	Text Overlay
Pseudo-Vertebrates			1	1	1			1	1	Text Overlay
Earliest Trilobites					1		1	1	1	Text Overlay
Shells		1	1				1	1	1	Text Overlay
Change of Order			1		1	1		1	1	Text Overlay

Table 3: Table showing interactions with Ambiguous Names

Icons

Similarly, self-explanatory Icons were also ignored. However, 'walk' being the first icon was interacted with by (8/9) users

Icon-Walk	2	1	1	1	1		1	1	1	Icon with Text Overlay
Icon-Jaws	2	1	1	1	1		1	1	1	Icon with Text Overlay
Icon-Gums	1	1	1	1	1	1	1	1	1	Icon with Text Overlay
Icon- Brain		1	1	1	1		1			Icon with Text Overlay
Icon- Fingers					1	1				Icon with Text Overlay
Icon- Runs		1				1				Icon with Text Overlay
Icon- Tools		1			1	1				Icon with Text Overlay
Icon- language	1	1	1	1	1	1		1	1	Icon with Text Overlay

Table 4: Table showing interactions with Clickable Icon Nodes

Visual Congestion

Visual Congestion was checked on the basis of 2 chapters: Chapter 5 and 6. They had all the above-mentioned interactive elements in them. The exact number of nodes were as follows:

- Chapter 5- 24 clickable, 48 Hover able, 2 static graphs
- Chapter 6- 16 clickable, 28 Hover able

In chapter 5, it was observed that the last few interactions (Post Age of Amphibians, node 13 in order) were skipped by a lot of users. Qualitative Feedback also reflected the same. It is tough to draw an early conclusion, but maybe introducing this chapter earlier might have invited more clicks. Users felt that 3 more intensive chapters are remaining and decided to quickly go through this chapter.

Cambrian Explosion	1	1	1	1	1	1	1	1	1	Text Overlay
Pseudo-Vertebrates			1	1	1			1	1	Text Overlay
Plus- Age of Invertebrates	1	2		1	1				1	Hidden Layer
Earliest Trilobites					1		1	1	1	Text Overlay
Plus- First Land Plants	1	1	1		1			1	1	Hidden Layer
Shells		1	1				1	1	1	Text Overlay
Plus-Glaciation	1	1		1	1					Hidden Layer
Animals Invade Land	3	1	1	1	1	1	1	1	2	Text Overlay
Plus-Age of Fish	1	1	1	1	1		1		1	Hidden Layer
Gymnosperms Dominate			1	1			1	1	1	Text Overlay
Forest and Land Invasion		2	1	1	1		1	1	1	Text Overlay
Amphibians on Land	1	2	2	1	1	1	1	1	2	Text Overlay
Plus- Age of Amphibians	1	1	2	1	1	1				Hidden Layer
Gigantism?		1	1		1		2	1	1	Text Overlay
Reptiles get Jaws		1			1	1				Text Overlay
First Herbivores		1			1			1	1	Text Overlay
Mammals?	1	2	1		1	1	1	2	1	Text Overlay
The Great Dying	1	2	1		1	1	1	1	1	Text Overlay
Age of Cycads	1	1					1		1	Text Overlay
Pangea Rifts		1	1		1				1	Text Overlay
Plus- The great predator		2	1		1	1	1	1	1	Hidden Layer
Angiosperms Dominate						1	1		1	Text Overlay
Mammals Diversify		1	1		1	1		2		Text Overlay
Great Predator Departs	1	1	1		2			1	1	Text Overlay

Table 5: Table showing interactions in Chapter 5, observed to check the Visual Congestion

However, in Chapter-6, constant Interest was shown throughout, despite some degree of complexity. Early results showed that the

number of interactions were not that overwhelming, and most users felt comfortable while going through this visualization.

Laurasiatheres	1	1	1	1	1	1	1	1	1	Text Overlay
Super Primate	1	2	1	1	1	1	1	2	1	Text Overlay
Major Global Warming		2	1				1	1		Text Overlay
Plus- Age of Mammals	2	2	1	1	1		1	1	1	Hidden Layer
Grass Appears	1	2	1			1		1	1	Text Overlay
Ungulates' Ancestor		1	1			1	1	1	1	Text Overlay
Carnivore Land Mammals		1	1		1	1	1	1	1	Text Overlay
Himalayas						1		1		Text Overlay
The Present Earth		1	1		1					Text Overlay
Whales Evolve	1	1	1	1	1		1	1	1	Text Overlay
Even Toed Ungulates	1	1		1	1			1		Text Overlay
Continuous Growth	2	2	1	2	1	1	1	1	1	Text Overlay
Herbs & Weed	1			1	1		1	1	1	Text Overlay
Dry Adaptation	1	1	1	1	1		1	1	1	Text Overlay
Snakes		1	1	1	1	1	1	1	1	Text Overlay
Herbivours Diversify	1	1	1	1	1		1	1	1	Text Overlay
Carnivores Diversify		1	1	1	1	1	1	1	1	Text Overlay

Table 6: Table showing interactions in Chapter 6, observed to check the Visual Congestion

Other Observations

- 'Plus' interactions were difficult to find. Only (5/9) users interacted with the first two Plus interactions
- Users interacted with Toggle and Buttons for fun initially. Some saw as many as 4 clicks.
- (6/9) users navigated back to Chapter 5 from Chapter 6. Other than that, only total 2 previous page navigations were observed.

We found some interesting observations in the user behaviour. The first observation showed that having an image/ graphic invited more clicks. Second, there was a relation observed with the Nodes and their Captions- with interesting and catchy captions attracting more clicks. This was observed with symbols too. Users showed a tendency to skip the recognisable symbols and captions. However, a completely different pattern was seen when the Human Chapter (Chapter 7) came up. When asked, the users remarked that 'Some relatable terms like Homo-Sapiens and Hominids' came up that encouraged them to interact with all the other nodes as well. The time spent on these chapters was relatively more. (Higher time per interactable node). This slightly contradicts the earlier observation. This brings me to another question: Is this behaviour of Interaction v/s Caption dependent upon the number of Interactive Nodes in an exploratory visualization?

Another observation was regarding visual congestion. Users were overwhelmed when the number of visual elements increased. This resulted in them losing interest in going through the visualization. Maybe in future versions, visualizations with different levels of complexities can be made to further testify this observation.

I do not claim that an interactive and exploratory visualization would 'always' follow the above-mentioned trends. This was also not the intention of the project. I am simply putting forward a few of my observations. **However, the observations can be carried forward to understand the 'User Behaviour in Interactive and Exploratory Visualizations' with respect to Inviting Captions, Layers of Interactivity and Visual Congestion.**

Prototype

The final prototype is made on **figma** and can be accessed from this link. It is recommended to set the settings to 'Fit To Screen'. It is best viewed for a Desktop or a Laptop. Please note that certain interactions like Hover will NOT work on a tablet or a mobile. The link is below:

(Link to the Prototype)

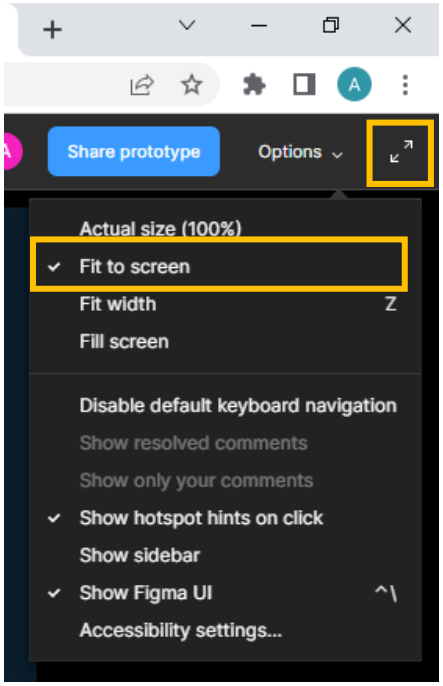


Figure 55: Recommended Figma Settings

Conclusion

It is challenging to put all the elements of Geologic Time in a visualization without making it overwhelming. However, certain key events (that are more important than others) can be demonstrated. We can find some similarities and patterns in these events that may help us gauge the cause-and-effect relationship of evolution is a comprehensive manner. Deep Time is far more intensive and 'Deep' than what can be represented. An event that has been ongoing since 4.56 billion years cannot and should not be understood in mere minutes. However, its importance has to be kept in mind.

The product tries to use a series of visualizations, linked together by a narrative to make Deep Time more understanding. It focused on the importance of visuals, interactions and explored the 'Exploratory Nature' of Data Visualization. It was also an attempt to visually represent the expanse of time in 2 dimension and experiential manner.

Reflections

The final outcome covered most of the things I wanted to convey through the research. Most of the users were able to understand this expanse of time that was highlighted by their urgency to find the 'Human Data Node' within the chapters. They were also surprised

with the frequency of the events that have happened in recent times (recent in Geologic Term) and the entire narration left them with some questions in their minds about the climatic changes like Ice Age. I was further able to identify a relationship between Text and Visuals in an Exploratory Visualization. The project also gave me an opportunity to understand the user behaviour with respect to different complexities of Visualizations. The visuals that appealed to me most as a designer, were considered to be overwhelming for a lot of users making me realise the importance of balance in such exploratory visuals. Sometimes what is visually appealing, might not always be the most suitable result for a generic audience that is not well-versed with the nuances of Visual Representation of data.

However, there are a few areas that I could have changed along with some that can be worked upon in the future to enhance the quality:

- The first and foremost being the implementation of a Coded Prototype. I vastly underestimated the scope of the project due to which I had to resort to a non-coded prototype.

- I spent more than required time in making the Data concise. There were several iterations over the data itself. A lot of time was spent in visualization of unnecessary data. The narrative should have been decided upon at an earlier stage.

- Due to limitations of the prototype, some enhance interactive techniques could not be implemented. Eg: Zooming, and enhanced transitions.

- I could have used a better metaphor than the life-span of a human being. Further, a relation between the events and the Metaphoric Time Scale could also be made visually, instead of only the narrative.

Future Scope

- Creating a Coded prototype to make it accessible to a wider range of audience

- Zooming into the Time Line of individual specie families can be added.

- Multiple layers of encoding can be added on the prototype that would help the audience filter the data they want to see and experience.

- Several click-based interactions can be replaced with a tool-tip in the coded prototype to reduce the amount of clicks

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