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Towards a collaborative methodology for interactive scientific data visualization

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Data visualization frequently provides audiences with novel semantic and computational presentations. How does a multifaceted team expand this scope by harnessing the power of visualization as a tool to think with? The NASA JPL/Caltech/ ArtCenter data visualization program demonstrates how scientific knowledge, shaped from data and theory, is equally co-constructed from diverse human perspectives. We will share case studies from Mars Rover Path planning and PIXLISE, a visual reasoning tool for understanding planetary geology. Working from source data through mixed media artifacts, these projects explore co-design methods for complex scientific domains with real-world applications. Our methodology emphasizes that all participants in the co-design process are both learners and experts. In this dynamic, the design and coding process are unique modes of critical discovery.

1. Background

The Data to Discovery Program has, over the course of a decade, investigated how experimental interdisciplinary teamwork in computing, art, co-design and research enable and critically engage scientific discovery.

This NASA JPL/Caltech/ ArtCenter College of Design collaboration approaches interactive data visualization in science and engineering as a unique mode of knowledge production. The authors Davidoff (UX Design and Research Manager at NASA Jet Propulsion Lab), Mushkin (artist and Research Professor of Art and Design at California Institute of Technology), Lombeyda (Senior Computational Scientist at Caltech and faculty at ArtCenter) and Hendrie (Professor, Interaction Design at artCenter) address two key objectives: (1) to develop the design of interactive data visualization systems in complex scientific domains with real-world, mission critical applications, and, (2) to develop a generative methodology, based on interdisciplinary practices, that prioritizes learning for interns and discovery for scientists and engineers.

2. Methodology

Human Centered Design (HCD) has been extensively discussed in interaction, software and communication design literature (Ware, 2009; Giacomin, 2014), however, it is infrequently employed in scientific data visualization practice. In addition, there are gaps in how students in design and computer science are trained to facilitate participatory sessions with domain experts in science and engineering. Understanding systems,

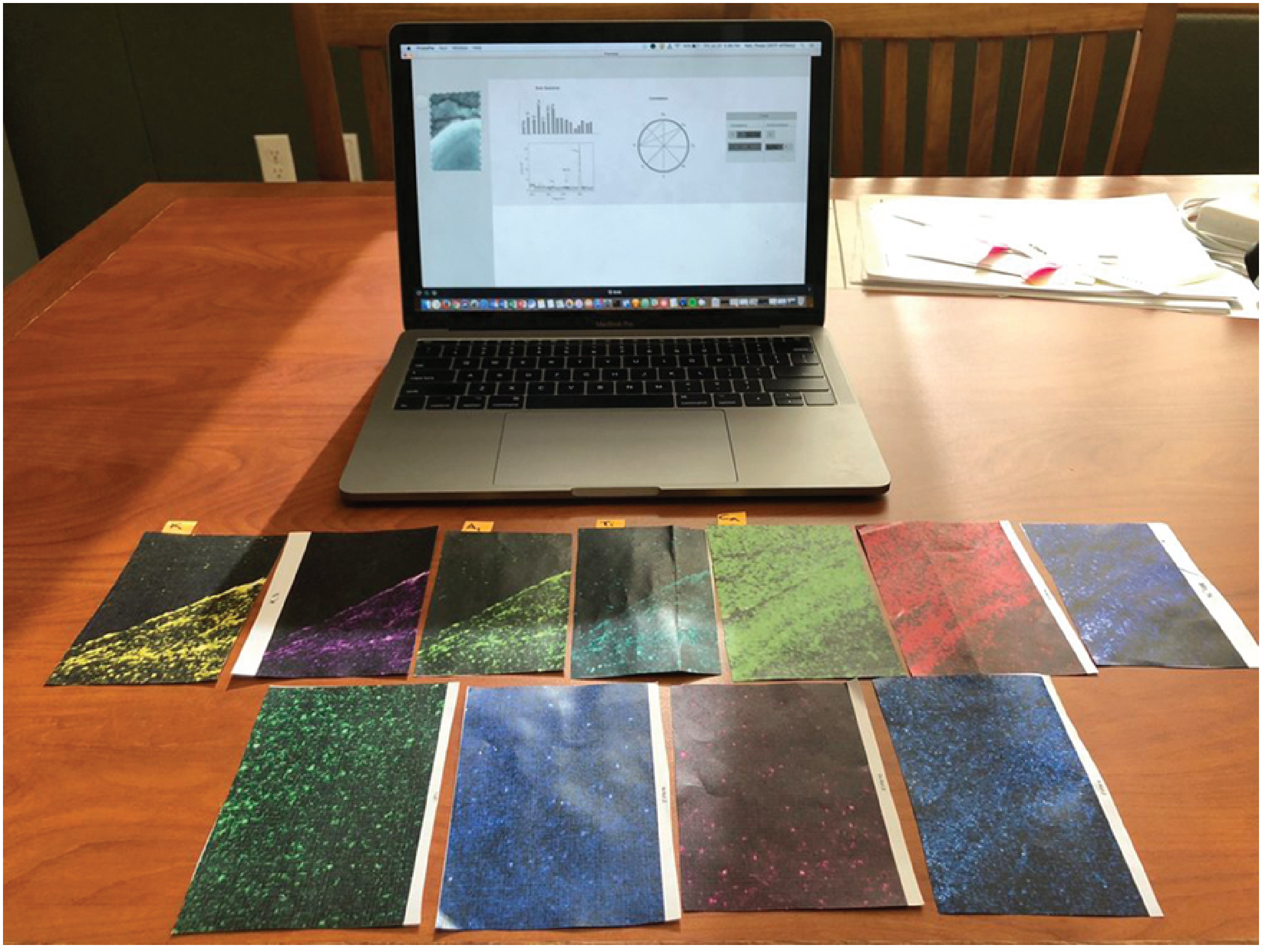


Figure 1. Example of mixed-fidelity prototype used in the development of PIXLISE. Courtesy NASA/JPL-Caltech/Art Center Data to Discovery Program/Mars 2020 Planetary Instrument for X-ray Lithochemistry (PIXL)

user experience and data design are often addressed in fragmented academic coursework, separate programs or specialized research. Our approach offers an opportunity to fill such gaps. Using HCD, we develop interactive data visualization as a specific medium and toolset for NASA JPL and Caltech scientists and engineers. By engaging HCD along with the semantics and pragmatics of interaction, we harness the power of visualization as a generative tool to think with.

Our framework, founded on diverse lineages of human computer interaction, participatory design, data visualization, 3D graphics, agile development, and media design (Davidoff & Zimmermann, 2007; Andersen, P. V., & Mosleh, W.S, 2020), aims to be educational and to generate effective solutions. Although many well documented methods exist, we query which techniques and processes are best combined to enable a discursive, generative process with a unique community of users and bespoke applications. Our approach engages frameworks for interaction and participatory design, as well as agile data and development methods. In our iterative "making to know" process, each step is a crucial moment of critical reflection, generative sketching, experimentation, galvanized by concrete proposals. Visualization is not just the project outcome. Used throughout, visualization is both the method and a tangible artifact.

Our ten-week summer program brings together interdisciplinary teams of researchers and faculty from NASA/JPL, Caltech and ArtCenter, with interns from around the US. The intern team is composed of two design and three computer science students. We work in parallel processes, proceeding from structured interviews and HCD discovery methods to co-creation of photos, sketches, videos, computationally generated and interactive media. On one side, using contextual inquiry methods, the students observe the scientists working with the data and prompt them to think aloud. Simultaneously, the students investigate the data sources and architecture, and then program draft visualizations. These methods are the backbone of an iterative process that cycles weekly. With insights gained from these processes, the students create increasingly interactive paper prototypes (see Figure 1, mixed-fidelity prototypes) and finally, completely coded products. This methodology respects not only the interns' development as literate facilitators in a dialogic engagement with scientists, but also the specific data, and the working hypothesis of the scientific team.

In this approach, information visualization is not just the project outcome; it is both the method and the tangible artifact. It exemplifies the practice which Davis and Vane (2019) call "externalization". In the "instantiation", visible and tangible forms of hypothesis and concepts underpin both scientists' and designers' practices. The steps, uses of source data, and the creation of mixed media artifacts demonstrate where scientific knowledge shaped from data and theory, is equally constructed from subjective human perception, socialization and acculturation. We believe these thereby inform a response to the fundamental ontological and epistemological question, "how do we know?" A significant design objective emerges in the context of Caltech/ NASA, where scientists seek not only to test or validate a hypothesis through known tasks, but to explore data to craft new hypotheses. With tacit knowledge that is often difficult to express, these experts have great influence on global scientific practices which leads to an additional program goal, namely, how to use design to question and influence the production of authoritative scientific knowledge. In this paper we offer two examples which focus on real world applications: RSketch and PIXLISE.

3. RSketch

3.1 Challenge

RSketch is a data visualization tool we developed in 2014–15 to help NASA/JPL engineers who drive the rover on Mars determine the safest and most efficient path. Driving the multibillion dollar robot from 150 million miles away is not an easy task. The engineers, known as ''rover planners'' (RPs), must navigate the rover Curiosity up and down steep slopes around unforgiving rocks and wheel-sinking sand to target locations determined by science teams. Their tools and processes were not intuitive. When we began working with RPs, they would spend about nine hours each day generating and simulating paths to send to the rover. The RPs would do much of the analysis and decision making in their heads. To start envisioning a path, they would type in low level command sequences which were compiled by a software called Rose. RPs would then use a second tool, Hyperdrive, to simulate these drive commands in a 3D environment with terrain meshes derived from satellite and rover imagery. Their workflow was from command to simulation, and it was repeated until the drivers found a plausible path.

3.2 Solution

To provide a streamlined analysis tool, the RPs first wanted a new, intuitive and visual way to create a path. After initial meetings with RPs John Wright and Frank Hartman (Mars 2020 Robotic Operations Subsystem Leads) to scope the work in the fall of 2014 and winter of 2015, we developed a solution in the summer of 2015. The project involved working intensively over 10 weeks with a student intern team of two designers (one specializing in UX/UI and the other in visual design) and one computer scientist. Our iterative methodology included weekly co-design sessions in which the RPs engaged with and helped sketch out our increasingly high-fidelity prototypes.

The RPs can thoroughly analyze terrain and consider uncertainty. Once the RPs finish the path, they can export it to the rest of the system (see Figure 2).

Over the next few years, the rover planner group developed this work into an application for visual sequencing, now part of the rover planning subsystem for the Mars 2020 Ground Data System. The tool we designed contributed to the larger geological and planetary science mission.

4. PIXLISE

4.1 Challenge

PIXLISE is a visual reasoning tool we have been developing since 2017 for planetary geologists and astrobiologists looking for signs of past life on Mars. Evidence is sought in Martian rock samples collected with PIXL, an instrument mounted on the Mars 2020 rover. PIXL produces high resolution mineral element maps which enable scientists to investigate extremely small geological features. These scientists' initial goal is to understand the spatial distribution and relationships between these minerals at different scan sites. Their ultimate goal is to detect geological evidence of life in leftover mineral patterns.

4.2 Process

After preliminary meetings with geologists and astrobiologists David Flannery and Abigail C. Allwood, we incubated the project through a working prototype in summer 2018. Our intern team included two designers with UX, UI and visual design experience and one computer scientist.

Working with seven geologists, spectroscopists and astrobiologists, we developed a visualization tool for

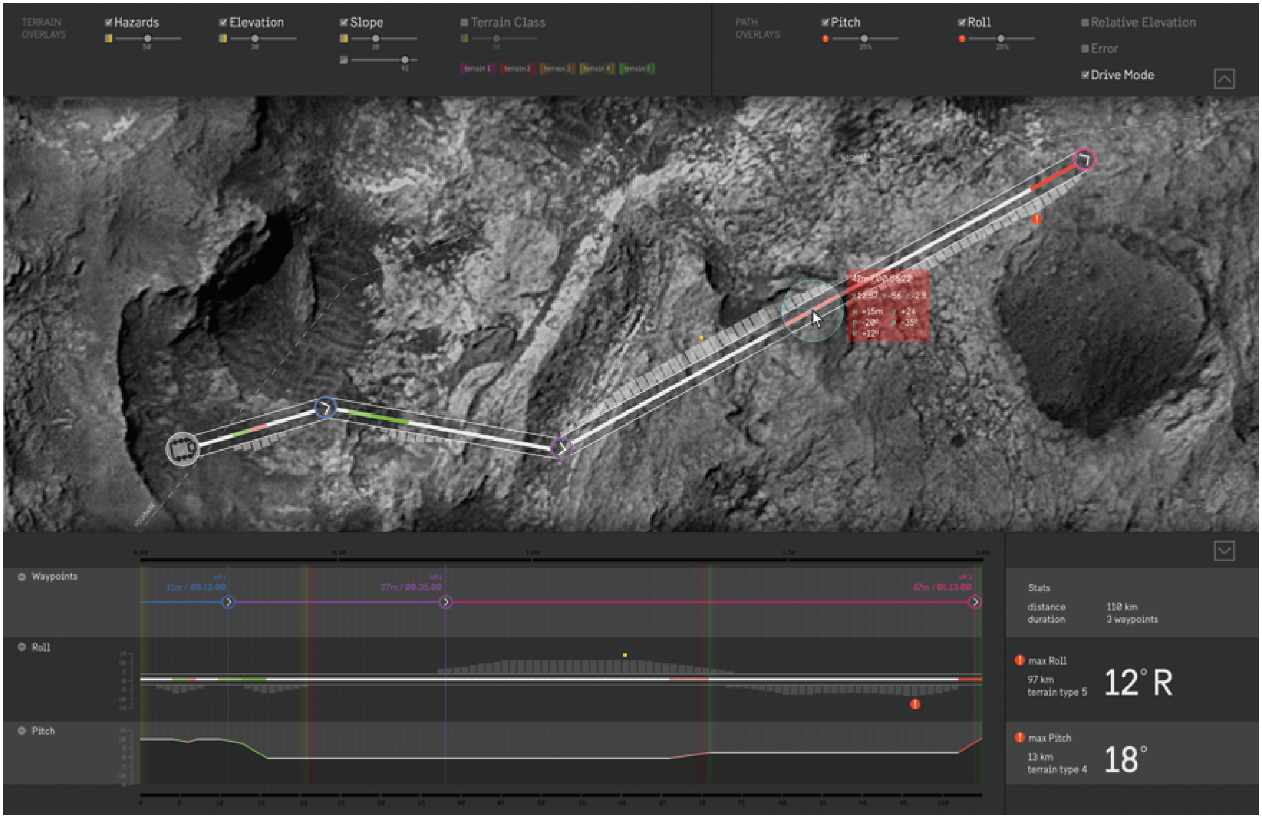


Figure 2. Instead of writing out commands, Rsketch enables RPs to drop a new waypoint directly on Mars landscape imagery sent from the rover's nav cam. Immediate changes can be made to the path without waiting for simulations. RPs can adjust, drag and remove waypoints with a click. Color and bars represent uphill pitch, downhill tilt and side to side roll. Pitch and roll affect speed; too much roll will cause the robot to tip over. A link plot allows analysis of pitch and roll against the other parameters along the path. Courtesy NASA/JPL-Caltech/Art Center. Data to Discovery Program / NASA/JPL Mars Rover Surface Operations

the scientists to generate, cross-compare, and analyze 2D element maps and x-ray spectra and correlate that information in a visual diagram. To design PIXLISE, our team engaged in contextual inquiry, co-design, and mixed-fidelity prototyping. Observing our scientists in their lab revealed the workflow, translations, tasks, and relationships within the team. Moving from a mindset of testing to one of co-design, we built mixed fidelity prototypes (using Adobe XD and Figma) to show real data in the context of a paper prototype.

4.3 Solutions

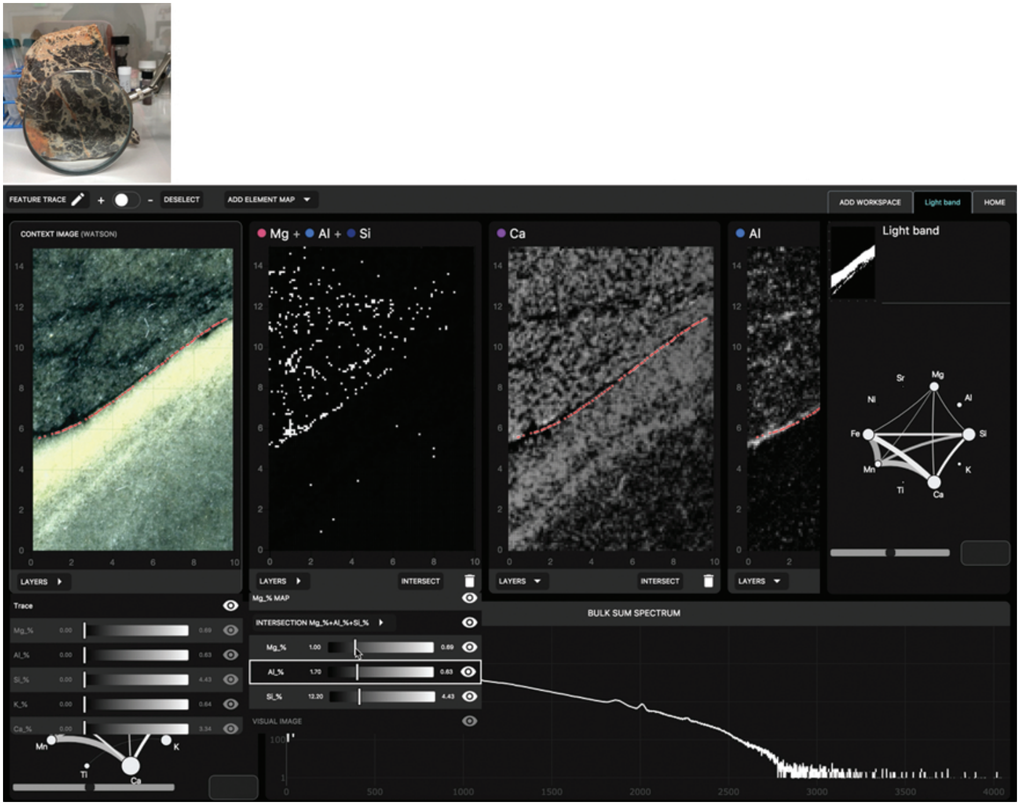
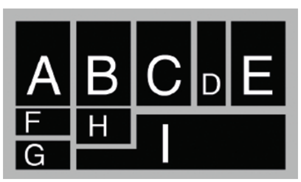


Figure 3.
(left) Actual Mars rock sample used to prompt scientists to think aloud about geologic pattern analysis. Courtesy NASA/JPL-Caltech/ Art Center.
Data to Discovery Program/ Planetary Instrument for X-ray Lithochemistry (PIXL)



PIXLISE workspace tool displaying: (A) context image, (G) global chord diagram showing abundance, correlations, and anti-correlation of major elements, and (I) bulk spectrum curve. When researchers select pixels of interest ("light bands") shown as red pixels in panels (A-D), the resulting (E) subset chord diagram is generated. From this subset chord diagram, researchers visualize correlations between key mineral elements. Each node represents an element (D) or [partial] element map of Aluminum (C), element map of Calcium, and ultimately (B) joint intersection map of Magnesium, Aluminum, and Silicone, with (H) manual balance of relative weights.

Our collaborating scientists need to understand dense images showing underlying, vastly diverse, geochemical or mineralogical similarity. In some images there are several thousand spatially oriented, blue dots, which the scientists analyze for continuity across the particular spectra. Through our iterative co-design process, we recognized that scientists conduct analyses by looking at groups of spectra, not singular spectra, something that is difficult to do in many mineralogical applications. By borrowing some Photoshop metaphors, such as a lasso or color fill, we created a tool for scientists to locate, select and examine relationships between areas (see Figure 3).

PIXLISE also includes a parametric heat map that enables scientists to develop and investigate hypotheses, such as questioning whether a particular mineral was at a particular location. By selecting key elements, scientists can interact with a parametric expression of the intersection of those elements. To facilitate discovery through trial and error, we created workspaces with individual element maps, as well as intersection maps. These workspaces enable scientists to compare a vast number of relationships, draw a line through correlations and create intersections.

Within the interactive chord diagram, the radius of the node is proportional to the abundance of that element in the mineral. The chords connecting the nodes are proportional to the covariance coefficient of those particular elements, with green for positive and red for negative. This allows scientists to simply glance at a sample and say, for example, that there is a high amount of calcium, a high amount of silicon, and a strong positive relationship between calcium and manganese.

Through our co-design process and feedback from scientists who use PIXLISE, we understand that the software provides a new, more efficient way for scientists to analyze and explore complex data. PIXLISE was adopted as the primary ground data interface for Mars 2020's Rover PIXL instrument (Schurman et. al. 2019; Flannery et. al. 2021; Ye et. al. 2021). It is also now part of the Australian PIXL Operations Center at the Australian Space Agency and Australian Research Council. It serves over 75 scientists, not including those in our initial collaboration.

5. Conclusion

RSketch and PIXLISE are just two applications out of the 27 interactive scientific data visualization applications that we have developed within the past 10 years of our program. During this time and through these projects, four key modes of inquiry, design and development have emerged as being especially relevant in designing interactive systems capable of tackling complex multi-variable correlated data:

1. Working with scientists and engineers in context provides the opportunity to understand how their research goals are enacted, in other words, how they seek to know, when they visualize and interact with their data. Such insights are a fundamental guiding principle for developing interactive data visualization systems for these researchers.
2. When working with complex scientific and engineering data over a short timeframe, agile modes of data exploration through pragmatic visualization enable developers to quickly understand data content and structure. This insight is essential for effective co-development of software with these researchers.
3. When representing complex data for research, it is necessary to tether modes of representation to interaction with the data. We focus on how representation and interaction with the data helps scientists and engineers answer their research questions.

4. Mixed fidelity prototyping or combining data with paper in prototypes helps scientists and engineers to engage with design prototypes at the early stages of the development process, and express the relationships between the data, their research questions, and emerging designs. This is a critical tool in our program.

While the short 10-week duration of our existing program has so far limited formal evaluations, such work is underway. We are currently focusing on analyzing how our methods of mixed fidelity prototyping and HCD ground design objectives and empirical experience. We also aim to further the dialogue on the roles that representational, interactive and dialogic design processes play in the development of authoritative scientific knowledge. Our ongoing research in digital humanities, art and critical theory focuses on interrogating artifacts, interactive systems, technologies and methods as areas of knowledge production.

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NASA/JPL Planetary Instrument for X-ray Lithochemistry (PIXL) team

Notes

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