# 1 SUPPLEMENTAL MATERIAL: PROCESS, ARTIFACTS, AND REFLECTION

Section 4 of the paper presents a high-level summary of the design study process. In order to support transparency and transferability of our research, we include, as supplemental material, a rich description of the four core phases of the study. For each phase, we detail the methods that we used and the artifacts that we created, and reflect on the learning and the questions that occurred along the way.

## 1.1 Preconditioning and Problem Formulation

Preconditioning and problem formulation [5] occurred over the course of 2 visits separated roughly 18 months apart in 2 years prior to the start of the design study. Research between visits was minimal and the visits were conducted in parallel with other visualization research projects. As such, we do not consider this a core phase of our design study.

The primary visualization researcher was already deeply familiar with the domain and had an established relationship with domain expert collaborators — having studied physics at [*anonymized*] and subsequently worked for the collaborators in computational astrophysics and astronomy visualization. We were motivated to conduct a design study in the domain as it offered a rich space to explore approaches to combining spatial and abstract visualization techniques. We entered this initial period of the design study with a general sense of problem space. Our goals during these two visits were threefold: 1) to scope out a project that met the criteria for a successful design study [5]; 2) to understand the broader research context including the roles and dynamics of the group, how research was conducted, and our collaborators current relationship with data and visualization; and 3) to clarify our role as applied visualization researchers, the objectives of our research, and the design study process.

During the visits, we conducted unstructured and semi-structured interviews with domain faculty, graduate students, and undergraduate students. We met with a total of 5 faculty, 7 graduate students and 3 undergraduate students. Interviews were conducted individually and in groups, and were nearly always recorded. Interviews were structured around learning about current research projects, how visualization was being used to answer research questions, and about the questions that domain experts were struggling to answer using existing approaches. During these visits, we also attended and participated in group meetings, attended talks and colloquia, and read relevant literature.

### 1.1.1 Artifact

The primary artifact of this phase was the problem formulation. The problem initially emerged in a group meeting with students and faculty during the second visit. A student was giving an update on his research. The group was examining a scatterplot, singling out a subset of points corresponding to a potentially interesting feature in the data. A faculty said something along the lines of *we should take a look at the corresponding galaxy images*. Under their current analysis pipeline, this would have required a lengthy process of identifying the points of interest, pulling the associated FITS files (likely from a remote cluster or supercomputer), and running a python script to render the appropriate images. Allowing domain experts to interactively query galaxy observation images via selections in plots would expedite this process and could greatly enhance their analysis.

The group meeting occurred at the end of the first day of a three day visit. The remainder of the visit was spent triangulating and further investigating the domain problem via discussions, brainstorming, and sketching with faculty, graduate students, and undergraduate students. We define the domain problem at three different levels: *High-level:* help understand how galaxies were formed and how they have evolved over time. *Mid-level:* help to verify computational models and to clarify what is being exhibited in observations. *Low-level:* support interactive analysis and comparison of real and simulated galaxy observations. Querying images via selections in associated metadata forms one of the core tasks of this interactive analysis.

### 1.1.2 Reflection

Entering the study, our collaborators had a lot of ideas for projects that could benefit from our visualization expertise, and they anticipated that we would be able to contribute broadly over a short period of time. It was therefore necessary that we spend some time up front discussing the components of design study research: the dual-goal of solving real-world problems *and* generating new visualization knowledge; the stages of the design process and the time and effort required by all team members; the exploratory nature and expectations surrounding final outcomes. Because of our existing relationship with our collaborators, we were able to have these conversations more honestly and transparently than was our experience in previous design studies.

It was also necessary to extend our collaborators' view of, and approach to data visualization for analysis. Astronomy visualization has, in large part, been dedicated to communicating scientific research and engaging the general public. This focus on presentation appears to have set the tone for what *visualization* translates to in research as well for our collaborators. While a project centered around scatterplots and images may have seemed initially underwhelming, our collaborators quickly saw the potential value in this kind of visualization for their analysis. In addition our collaborators tended toward a technique-driven approach to visualization: generating visualizations using the latest, state-of-the-art techniques, and seeing if the results yielded any new insight. Thus, our goal during these visits was also to transition their thinking to a more task- and question-driven approach to visualization design.

## 1.2 Learning About Galaxy Observation Analysis

Following the preconditioning and problem formulation, the first core phase of the design study was devoted to learning about the analysis of galaxy observation data. Our goals for this phase were to understand the data and tasks associated with analyzing and comparing real and simulated galaxy observations, and to obtain an initial dataset. The phase spanned 3 months, and was structured around a single visit to [*anonymized*].

The visit consisted of more unstructured and semi-structured interviews with 4 faculty, 4 graduate students and 2 undergraduate students, all of whom we had worked with in previous visits. Interviews were structured around understanding our collaborators current statistical and visual analysis pipelines. In several cases, we conducted think-alouds in which we asked our collaborators to walk us through their analysis of existing plots and images. We additionally participated in a group meeting with faculty and students in which we demo-ed existing, related tools (namely yt and Glue), and then brainstormed, via sketching ideas on a whiteboard, how such tools could be extended to support the existing domain problem. The brainstorm included a discussion of data and tasks.

### 1.2.1 Artifacts

The primary artifact of this phase was an initial data and task abstraction, which we continued to develop and refine over the course of the study. The final abstraction is presented in Section 5 of the paper. This initial abstraction formed the basis for our visualization design work. A secondary artifact of this phase was an initial dataset. The dataset comprised a collection of images — a set of two images for each observation — and a table of quantitative data attributes derived from analyzing the images.

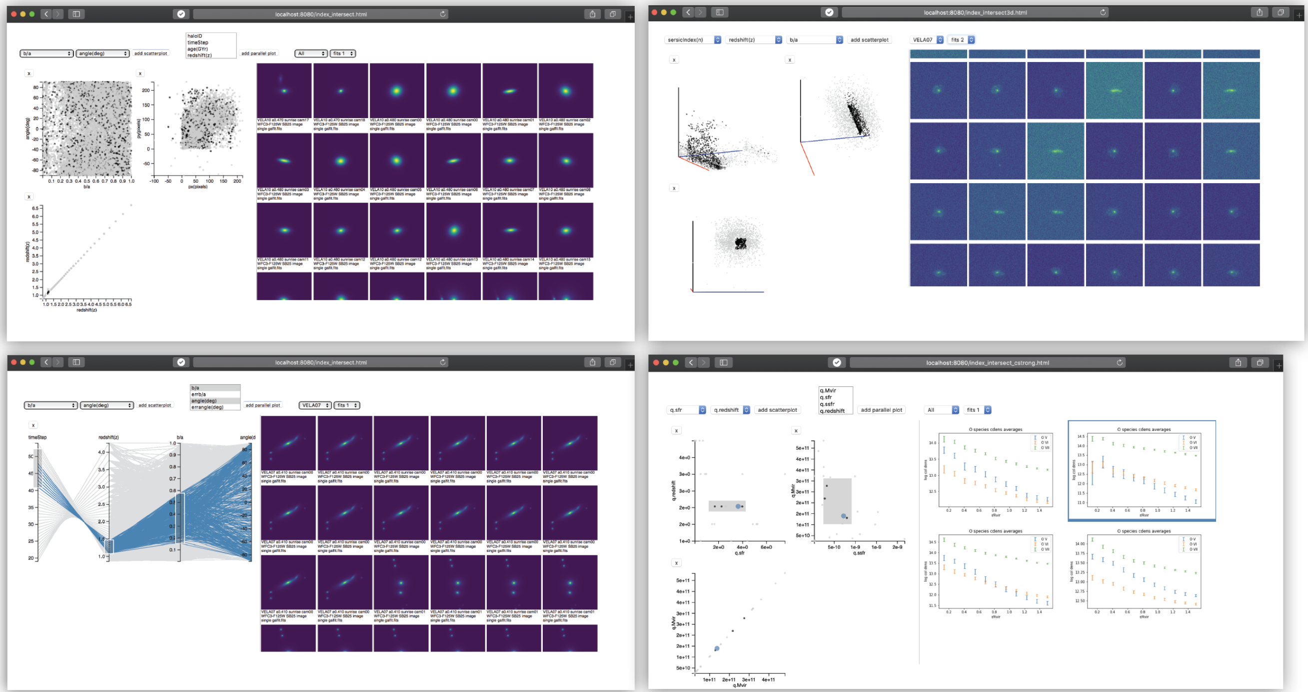

Figure 1: four iterations of the technology probe: *(top left)* querying images via selections in various scatterplots was a core function of the system; *(bottom left)* parallel coordinate plots proved to be effective as interactive legends for filtering data across 3+ dimensions; *(top right)* interactive 3D scatterplots emerged as a potential future visualization research opportunity; *(bottom right)* we used the technology probe to experiment with a range of datasets.

### 1.2.2 Reflection

We approached the domain problem, and thus the initial data and task abstraction, as a way to probe the problem space in the hopes that it would lead to more interesting visualization research opportunities. As we progressed, however, it became evident that a standard linked-view approach could greatly enhance our collaborators analysis. This presented us, the visualization designers, with a conflict: do we pursue novel visualization design spaces, which may not be nearly as relevant or effective for our collaborators? Or do we focus our efforts on developing a validated design that combines and handful of established approaches, and could potentially lead to the confirmation or refinement of existing visualization design guidelines [5]? While perhaps the more risky route from a visualization research perspective, we ultimately decided to go with the latter option.

We had assumed that obtaining an initial dataset would be straightforward, given the abundance of data and the data-sharing culture within the astronomy and astrophysics community. Unlike, for example, medical or public health data, astronomical data are hardly ever sensitive, confidential, or vulnerable to being weaponized. In addition, astronomy research is often publicly funded, with the requirement that the resulting data be made publicly available and accessible. We were therefore surprised when obtaining these data proved to be a challenge. Rather than being directed to a specific dataset, we were directed to numerous sources from which a representative dataset could be curated – a non-trivial task that required extensive domain knowledge, and thus multiple rounds of input from our collaborators. We suspect that this reflects how datasets are curated within this domain. Researchers have an enormous amount of data at their fingertips. In designing an experiment, there are often multiples suitable datasets from various sources to curate from. This greatly expands the breadth of possible research, but presents challenges when trying to obtain a representative sample of the data to test and develop with.

## 1.3 Exploring the Visualization Design Space

Once we had arrived at an initial data and task abstraction, and had obtained a actual dataset, the next phase was devoted to exploring the space of visualization design. Our primary goals for this phase were to elicit design requirements, and develop a initial design. We also used this phase to continue to test, develop and refine our data and tasks abstraction, and to probe for potentially more interesting visualization opportunities. The phase spanned 6 months and was structured around 2 visits to [*anonymized*], approximately 2.5 months apart. During this phase we collaborated with 3 of the faculty and 3 of the graduate students from our previous visits, and 1 new collaborator – post-undergraduate researcher – whom we worked closely with for the remainder of the study.

In preparation for the first visit, we developed a bare-bones technology probe, based on our initial data and task abstraction and the results of our preliminary discussions, sketching, and brainstorms, and featuring the initial dataset. The initial probe, shown in the Figure 1 *(top left)* was developed in D3.js, and supported only the basic functionality for generating scatterplots and parallel coordinate plots, and for querying images via plot selections (which we implemented via brushing). Over the course of the two visits, we used the technology probe to brainstorm and experiment with new features, functionalities, and interactions, and to explore possible applications to a range of datasets. Through the iterative development of the technology probe, we were able to home in on the set of features, functions, and interactions that best supported the tasks at hand. These features and interactions formed the basis for our initial design. The technology probe also provided a platform for gathering initial informal validation, e.g. in the form of *"Ive been asking for this for 20 years!"* During this phase, we also connected with the lead researchers of the two primary astronomy visualization and analysis packages (yt [6] and Glue [1]), to explore the possibility of developing our system as package extensions.

### 1.3.1 Artifact

The primary artifact of this phase was a technology probe, which we iteratively designed and developed, and which heavily informed our initial design. Screenshots of four iterations of the technology probe are presented in Figure 1.

### 1.3.2 Reflection

As we found in our previous design studies [*anonymized*], the technology probe proved instrumental to engaging our collaborators and to creating a conducive and productive environment for investigating and testing ideas, learning about the domain and about our collaborators, and eliciting feedback and a broad range of ideas. The technology probe also allowed us to explore potentially more interesting visualization research opportunities; one of which was the use of interactive 3D scatterplots.

Interactive 3D scatterplots play an important role in our collaborators' research. They have been critical to discovering fundamental features and planes in galaxy observation data, and there is current interest in using them to look for more complex coherent structures and surfaces. As one collaborator put it: *"I've built my career analyzing 3D scatterplots"*. These plots, however, are inherently problematic. They introduce issues of occlusion and spatial ambiguity, among other things. Approaches within the visualization community often turn instead to 2D projections of 3+ dimensional space, sometimes using animated transitions showing the original higher dimensional space in order to provide additional context [2,3]. Building on existing work in this space [4], we see this collaboration as an excellent opportunity to further investigate the value of 3D scatterplots for analyzing and detecting features in 3+dimensional data. Is there anything that we can learn from this domain?

An underlying question throughout this design study was: *why hadn't this system already been developed?* Our design was an obvious approach using thoroughly-established visualization techniques. When we brought up the question in a discussion with three faculty collaborators, they remarked that designing and implementing such a system was not an appropriate project for an astrophysics graduate student. When asked why the feature had not been implemented in existing analysis packages, they said they didnt know. While this was the extent of inquiry, we see this collaboration as an excellent opportunity to explore potential barriers of adoption faced by domain researchers and practitioners surrounding the use established visualization techniques. It would also be interesting to investigate how primary analysis packages are developed, what features are incorporated and why, and how researchers approach using these packages. How much of their analysis, and thus research, is guided by the capabilities of existing packages? Are there ways to design these packages that better support user-guided analysis? Can visualization research learn from or contribute to this area?

## 1.4 Iterative Design and Development

The final phase of the study was devoted to implementing our design. Our goals for this phase were to translate our findings, and the results of our technology probe, into a usable, deployable visualization prototype, and to evaluate the prototype with domain experts via several different case studies. This phase spanned the last 4 months of the first stage of the study.

During the first 3 months of this phase, we met remotely on an either weekly or biweekly basis with one primary collaborator who was a post-undergraduate researcher. Over the course of the meetings, we iteratively designed, developed and refined the prototype using a case study that was central to the collaborators focus of research. During the final month, we met remotely with two collaborators, the post-undergraduate researcher and our primary faculty collaborator, to prepare for and later to conduct the two case studies presented in Section 7 of the paper.

During this phase we also further explored the possibility of developing the prototype as extensions to the two primary astronomy visualization and analysis packages, yt and Glue. We met remotely with each of the lead researchers of these packages to discuss a development plan, and we attended and participated in a developers workshop for yt. The workshop allowed us to investigate the ways in which our system could be meaningfully incorporated into the existing yt framework. It also provided an opportunity to interact with other astronomers and theoretical astrophysicists working in similar areas: to triangulate our study findings, gather informal feedback and validation, to gather new case studies, and to connect with potential future collaborators/users of the system.

### 1.4.1 Artifacts

The primary artifact for this phase is the implementation of our design in GalStamps, presented in Section 6 of the paper.

### 1.4.2 Reflection

A significant amount of time during this phase was spent wrangling and pre-processing data for one of the case studies. While this is a reported pitfall of design study, we've found that some degree of wrangling and processing is often necessary when visualizing new kinds of data. Rather than viewing this as necessary overhead, we wonder if there are ways that we can leverage these efforts for our research. For example, are there patterns in wrangling and pre-processing that we can characterize and provide guidance around?

Once we had finished wrangling and pre-processing the case study data, it became evident that our collaborators needed slightly different 2D scalar field data in order to investigate their initial research question. Our collaborators often take an iterative approach to research — trying one approach, seeing if it's informative, and then either iterating on the approach or trying something else. When introducing new kinds of visual analysis that help to answer new kinds of domain questions, a certain amount of iteration may be needed to perfect the investigation (articulate the question, prepare the data...). The was not a surprising result. Like many domain researchers our collaborators often take an iterative approach to answering their research questions — trying something, seeing if it's informative, and then either iterating on the approach or trying some else entirely. This presents a challenge for design study, in which the goal is often to use visualization to help domain experts ask new questions of their data, or see their data in a new way. How can we support this iterative refinement of the question while also evaluating and validating our results?

## References


[1] C. Beaumont, T. Robitaille, A. Goodman, and M. Borkin. Multidimensional data exploration with glue. In *Proceedings of the 12th Python in Science Conference*, p. 8, 2013.

[2] N. Elmqvist, P. Dragicevic, and J.-D. Fekete. Rolling the dice: Multidimensional visual exploration using scatterplot matrix navigation. *IEEE transactions on Visualization and Computer Graphics*, 14(6):1539–1148, 2008.

[3] S. Liu, B. Wang, J. J. Thiagarajan, P.-T. Bremer, and V. Pascucci. Visual exploration of high-dimensional data through subspace analysis and dynamic projections. In *Computer Graphics Forum*, vol. 34, pp. 271–280. Wiley Online Library, 2015.

[4] H. Sanftmann and D. Weiskopf. 3d scatterplot navigation. *IEEE Transactions on Visualization and Computer Graphics*, 18(11):1969–1978, 2012.

[5] M. Sedlmair, M. Meyer, and T. Munzner. Design study methodology: Reflections from the trenches and the stacks. *Visualization and Computer Graphics, IEEE Transactions on*, 18(12):2431–2440, 2012.

[6] M. J. Turk, B. D. Smith, J. S. Oishi, S. Skory, S. W. Skillman, T. Abel, and M. L. Norman. yt: A multi-code analysis toolkit for astrophysical simulation data. *The Astrophysical Journal Supplement Series*, 192(1):9, 2010.