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Independent and Collaborative Visualization Tool Development

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Abstract

Visualization is thriving as an academic discipline. However, the development of visualization heavily relies on applications in other base sciences. We examine the visualization development process, which includes both collaborative development with domain scientists and independent development by visualization tool developers, and tell the behind-the-scene stories of FluoRender.

Visualization is a burgeoning branch of scientific studies, nurtured by experts from originally diverse backgrounds and disciplines of computer graphics, software engineering, natural sciences, social sciences, and arts. Sitting at the juncture of multidisciplinary interactions, visualization has demonstrated its independence as a self-sustained academic discipline. The excitement, as well as growing pains, has never been felt more profoundly by researchers in recent years. The dependence of visualization research on other base sciences has been even more accentuated, as evidenced in the growth of application-concentrated conferences including IEEE VAST and BioVis, the increasing attention to application papers,[1] and the emphasis on user studies.[2] The argument between the dependence and independence of visualization as a science can be an overly simplified discussion considering the trend in scientific research, while the same question may be asked in many interdisciplinary fields. After all, the advance of human knowledge as a whole is the common goal of all scientific disciplines, the merge, division, and collaboration among which are merely an instrument for achieving the goal. Using the words of visualization researchers, the development of visualization can be described as a function of high-dimensional space; a decomposition depending on discrete multidisciplinary bases already distorts it; a simple projection to onedimensional (1-D) is undoubtedly misleading.[3]

Although a comprehensive assessment of all visualization research is understandably impossible, here we attempt to slice a profile of the high-dimensional space by examining the developmental process of a successful visualization tool for biomedical research, FluoRender.[4] Especially, we pay attention to the relationship between domain experts and visualization developers in the collaborative development of FluoRender, as well as in the mutual influence between FluoRender's value in data visualization as an independent tool

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and its service to advance biomedical research. Some of the viewpoints, insights, and behind-the-scene stories are less likely to be discussed in either technical and application publications by visualization researchers, as well as publications by researchers in biomedical sciences. Although our sample space is far from sufficient, we hope this article serves as an inspiration to researchers by providing fresh examples from our viewpoint.

REACH OUT

Identify Potential Users

In 2008, Chi-Bin Chien, a neurobiologist and expert on transgenic zebrafish research at the University of Utah, discussed with the authors on building a new tool to visualize the 3-D images acquired from confocal microscopy. Although there have been several tools from both academic and commercial institutions that could accomplish the basic requirements, Chi-Bin realized that a better tool was not only possible but also necessary.[5] The discussions with Chi-Bin and his lab started the FluoRender project. Domain experts reaching out to visualization experts with specific aims is the most common scenario that starts a visualization project. As our project developed, we, the visualization researchers, also took initiative and reached out to biologist users, as we presented our work at microscopy conferences, open-house events, and social media websites. However, the success and popularity of FluoRender are more often gauged with the requests from existing and potential users. A continuous flow of ideas and challenges introduced by potential users maintains the momentum for development and drives the project to grow vigorously. Therefore, we need to recognize these potential users from initial interactions.

We generally categorize the sources of potential collaborators into four groups according to the strength of connection to visualization researchers. **Scientists from the same institute** are most easily accessible and tend to become strong supporters once the initial collaborations prove to be productive. The success in collaboration with Chi-Bin's lab advocated FluoRender among Chi-Bin's colleagues via demonstration and education of the software. Although biologists often group according to the focused sample species of their research, such as zebrafish, fruit flies, mice, etc., the application of microscopy and visualization technologies can easily carry over from one group to another, especially when interactions among scientists are unhampered by geographical distances. We have since established a close collaborative relationship with Gabrielle Kardon and her group at the University of Utah, who are experts on mouse musculoskeletal systems.

With the influence of FluoRender increasing, researchers outside of our institute began to hear about it. **Researchers introduced by peers** may not start with a comprehensive view of the capabilities of a visualization tool. It is our responsibility to quickly understand their needs and provide solutions based on both existing functions and potential improvements. It is interesting to mention that sometimes the chain of advocators goes around and back. Olympus, a manufacturer of microscopy imaging devices, had collaborated with Chi-Bin's lab for microscope lens tests. To demonstrate their newly developed lenses with improved resolving power, they needed an imaging tool to render and compare results with the most faithful representations of data. They eventually chose FluoRender and included visualization results generated with FluoRender in the advertising material, as they regarded

FluoRender superior at showing high-resolution details. Later, Olympus demonstrated a two-photon system at the University of Utah. Holly Holman, a biologist in the Department of Bioengineering studying the inner ear nervous system, used the two-photon microscope to scan several 3-D samples. When Holly asked the Olympus sales representative about recommendations of a visualization tool for viewing 3-D scans, she was surprised that the sales representative suggested FluoRender, which she found was developed right next door. After learning more details from us, Holly has since become a regular FluoRender user and advocated FluoRender whenever there was a chance.

General users often heard or read about FluoRender from publications and conference presentations. The enormous quantity of scholarly publications determines that every researcher can only concentrate on a limited collection of topics as both author and reader. Venues focusing on visualization techniques are so far not well exposed to the biomedical research community, as nonvisualization experts prioritize seeking practical direct solutions over exploring technical details for visualization tasks. We have collaborated with biologist users of FluoRender for publications on both visualization focused and interdisciplinary venues, including IEEE VIS, BioVis, and BMC Bioinformatics. However, major exposure of FluoRender to the user community depends on the publications by biomedical researchers who documented the use of FluoRender as part of their scientific research protocols, as well as acknowledging its use for generating images and videos. The connection of FluoRender to certain fundamental research helped the growth of its user community. For example, Kei Ito's lab at the University of Tokyo studied the clonal composition of the Drosophila brain, which lead to the design and publication of a nomenclature of the neurons as a biological tool.[6] The recognition of Kei's Drosophila brain atlas among neuroscientists studying the Drosophila brain popularized FluoRender, which was used to interactively visualize the many-channel volume data set (Figure 1).

Finally, there is the Internet and the social media built on top of it. We have been maintaining an array of FluoRender web accounts for information and tutorial video posts, as well as user connections. However, accurate statistics on **users who found information on FluoRender via web search** are difficult. Unlike paid software, freeware users often feel reluctant to reach out to the developers and discuss their experience. Instead, we actively search the Internet and seek information about how users may have used FluoRender. For example, we once found a biology lab in a university posting the use of FluoRender as part of their lab's protocols for experiments. The protocols included detailed steps of how to operate the tool with screenshots to demonstrate its use. We also found certain issues in the protocols, where multichannel data were handled inefficiently. We contacted them promptly and helped design a more efficient workflow of data visualization. In turn, they became more involved and later helped identify FluoRender issues for us.

Initial Exchange of Ideas

The initial exchange of ideas between domain experts and visualization tool developers is critical and sometimes determines the next developments. It was fortunate that our initial collaborations with Chi-Bin's lab worked out smoothly, as Chi-Bin had a clear view of what biologists wanted and how much contemporary computer graphics could achieve. From later

conversations with Chi-Bin, we learned that he had a sibling who worked for NVIDIA and led the design of graphics chips. Despite not being an expert on GPU programming himself, Chi-Bin definitely saw the leaps of GPU performance, plus the extensive availability of programmable pipelines and 3-D textures, which finally allowed us to focus on practical matters in biological data visualizations. Previously, much effort was made on tweaking code for enhancing volume rendering frame rates and circumventing hardware limitations.

However, the situation where collaborators immediately work together with a good knowledge of the requests and capabilities of each other usually cannot be taken for granted. In many cases, domain experts may engage visualization researchers without a well-defined problem set and goal. On the other hand, we should not readily assume and predetermine the most appropriate visualization methods for domain experts. To overcome the difficulties arising from the misalignment of expertise among collaborators, effective communication is needed.

COMMUNICATE

Watch out for Jargon

Kirby and Meyer encouraged bilingual collaborations.[7] Although the lack of knowledge about collaborators' highly specialized vocabularies can be frustrating, the forefront barrier preventing effective communications in multidisciplinary collaborations is actually from jargons disguised as frequently used words. Since the same word can have many meanings within different technical contexts, extra care is needed to detect the potential origins of misunderstanding and explain them clearly. This is especially important for words that we have used so often that are forgotten as jargon. For example, for biologists, "visualization" can mean physically highlighting a biological structure under a microscope using a staining technique, such as fluorescently tagging it using the immunochemistry method. A visualization tool can, therefore, mean a biological method to biologist listeners. Further explanations or replacing it with "3-D imaging software" can clarify such misunderstanding effectively.

Acronyms with multiple definitions can also cause misunderstandings. For example, it may be inconsiderate to refer the expectation-maximization algorithm as "EM," without noticing that a biologist, or a microscopist especially, can very likely mistake it for the electron microscope, a physical tool to acquire images.

Acronyms used frequently by visualization researchers can be unknown to collaborators: a GPU has been used in every modern computer, but the acronym itself is in fact much less popular than "CPU." For users who are not interested in the technical details about their differences, using CPU as a comparison to explain the GPU is satisfactory. Paying attention to such details in collaborative communications helps establish mutual respect and trust.

Bring Ideas but be Ready to Adapt

Visualization tool developers are expected to fill in the gaps and materialize the crude concepts by making prototypes for domain experts. We often feel confident for methods that are familiar or proved to be effective in the visualization community and expect similar

acceptance by domain users. However, adaptions are frequently needed. In the early stage of FluoRender development, we presented a prototype tool with a 2-D transfer function widget panel for adjusting the volume visualization results of confocal data.[8] Although the 2-D transfer function widget design has been well received in the visualization community, biologist users found it difficult to adjust in practice. Despite its flexibility to extract salient features from volume data, the transfer function widgets were abandoned for a simplified design after working with the collaborators from Chi-Bin's lab. The biologists found the joint histogram of intensity and gradient magnitude unintuitive. In addition, the complexity of manipulating the transfer function widgets was unnecessary for their data. To maintain the essence of a 2-D transfer function and improve intuitiveness for adjustments, we parameterized one rectangular transfer function widget and only used sliders plus numeric inputs to change its shape. The names of the parameters were also determined by considering our collaborators' suggestions.[5]

The collaborations with biologists have been full of surprises, as visualization designs overlooked by visualization researchers at first might contain significant values discovered by users. In FluoRender, we render a volume using the slice-based method. Initially, it allowed us to intermix RGB fluorescent channels in 3-D. The capability to intermix more than three channels was not initially considered, as the graphics hardware then was barely sufficient to support interactive viewing of RGB volumes from common fluorescence microscopy scans. Just several years later, users from the Ito lab told us that they were able to visualize 100 channels using FluoRender on a Geforce GTX 680 graphics card, one of the first consumer cards equipped with 4-GB of graphics memory. They also told us that no other visualization package could achieve that success. In retrospect, we did not intentionally choose the slice-based method for many-channel intermixing. However, the method allows a simple shader code to handle only one channel at a time and intermix channels at each slice. With the processing capacity of graphics hardware increasing, it was only a matter of time for the most adventurous users to explore into the "out-of-spec" territory, as long as FluoRender's data management did not limit the number of channels. Based on the feedback, we further improved the interactivity of many-channel visualization with a streaming process.[4]

Identify Collaborators' Talents

A successful project results from the collaboration of a group of multitalented people. Identifying each collaborator's talents and turning them into productivity has practical significance. It is unfair to assume a collaborator to be an expert only at his/her scientific domain, as we have worked with biologists who are also illustrators, musicians, poets, and even software developers. In visualization tool development, designs that appeal to a user's extraprofessional talents can produce exceptional results.

Many FluoRender users regularly work with Adobe Photoshop. Photoshop is a popular tool among bioimaging experts because it is not only handy for adjusting images in research but also for artistic expressiveness in daily life. We designed the interactive segmentation functions in FluoRender after the brush tool in Photoshop, both used for selecting and editing.[9] It requires more skill and patience when 3-D data are processed. However, users

already familiar with Photoshop often feel the FluoRender brush tool intuitive and quick to master.

For example, researchers of Kardon lab studied the limb musculoskeletal development. They found the mutation of a gene called TBX3 can cause abnormal muscle development. Using mice for their experiments, the lateral triceps and brachialis muscles are distinct in healthy samples; while in the mutant mouse, the two muscles are fused and indistinct, limiting the forelimb's function (Figure 2). Further research linked the muscle development anomaly to the ulnar-mammary syndrome.[10] FluoRender was instrumental in identifying and visualizing the anomaly in this study. In fact, the researcher who worked on this project had to brush select a series of 3-D scans after each experiment. We worked together on the details of the FluoRender brush so that it worked similarly to an artist's tool. The work of segmenting the muscles from 3-D data turned out to be rather enjoyable instead of laborious. Depending on a user's knowledge and familiarity about Photoshop, the experience can be quite the opposite. However, if we can identify the artistic talent of a person and design the tool accordingly, the results always amaze us. Consequently, the work of Kardon lab was featured on NIH Director's blog, where the use of FluoRender was also highlighted.[11]

Be Ready to Help

Most of our long-term collaborations were in fact not planned out from the beginning. We have many users who contacted us because they got stuck on hardware and system issues. The most common scenario has been that someone could not launch FluoRender because no dedicated graphics hardware was installed on the computer. Subsequent inquiries on configurations for a new computer have also been frequently received. Customer-service-like requests are not directly related to the development of a visualization tool and may seem to be distractive for an understaffed academic group. However, we are ready and happy to help users as long as a significant amount of time is not involved. No matter how trivial or irrelevant an issue is, it could become the entire experience by a frustrated user. Making sure that the details are attended to allows domain users to focus on their scientific questions, which in turn can become visualization development opportunities.

In the development of FluoRender, file format support has been time consuming, as there are numerous microscopy formats, each with a set of variations. Since file format support is not considered as visualization research, maintaining an original code base for loading commonly used formats may be overlooked. Furthermore, manufacturer provided APIs and dedicated microscopy format libraries, such as BioFormats for ImageJ,[12] alleviate visualization developers from directly coding file readers. However, specialized use cases may demand familiarity of a format, so that its reader can be customized for visualization applications. The microscopy core facility at the University of Utah was among the early adopters of the Prairie/Bruker two-photon system. We were invited to work with engineers from Prairie/Bruker to add format support into FluoRender. The format is open, using the XML standard to index TIFF tiles of a scan. Initially, writing our own reader was out of necessity and willingness to help, as official or third-party readers were not available. Nevertheless, it provided us collaboration opportunities in the long run. First, we were among the first to deliver a visualization tool supporting the Prairie/Bruker two-photon

system. When the microscopy format was revised later, we were able to provide users with an up-to-date reader ahead of other imaging tools. Second, the open format enables customization by coding experiment-specific information into the XML files. We have been working with experienced users to make FluoRender more intuitive for user-customized formats. Finally, users may take advantage of a technical feature in a nonstandard fashion. For example, a moving stage of the two-photon system is designed to scan a large biological sample by mosaicking. Instead, microscopists of the Utah microscopy core scanned separate samples on the stage. These live samples need to be compared against each other. Scanning multiple samples on one stage was not only time efficient but also necessary to assure the same controlled environment. Unfortunately, standard Prairie/Bruker readers made it difficult to visualize the results, because they were interpreted as a single mosaic instead of separate scans. The familiarity with the format allowed us to modify the FluoRender reader code and separate a large scan into individual channels (Figure 3).

EVALUATE

The development of an independent tool contributing to scientific advances is a long-term process. Although time might be the ultimate measure of success, after all, short-term evaluations are possible and necessary. We have summarized our methods to evaluate the development of FluoRender.

User Studies

Unlike a formal user study with predesignated tasks and questions, we prefer observations of real users operating FluoRender for realworld work without setting goals to validate specific features. In fact, such undercover user studies are commonly user-initiated when they start learning the tool, or when they have encountered difficulties and would like to seek help. Then, domain users and visualization developers can sit together to walk through workflows and discuss issues. On one hand, users get familiar with the tool, and developers receive the firsthand feedback on the other. The development of FluoRender's transfer function and brush tool both used this method to detect issues and improve user experience. Meeting and discussion were repeated for each development iteration to fine-tune the details. Only when the purpose of such interactions is to improve user experience, can users liberally express their thoughts on both pitfalls and strengths of a tool, which are not biased by a preordained aim to prove success.

User Recognition

Visualization developers should look beyond own publications to evaluate the success of a tool. The recognition and popularity are also demonstrated as support and achievement by users. The FluoRender project has been popularized through free advertisements by users; we received numerous support letters from keen users when we applied funding to continue its development; users of FluoRender have used it to win image and visualization contests; some of the most successful applications were also featured on journal covers and scientific websites to reach the general public.

User recognitions are also quantitatively evaluated by the citations and acknowledgment of a tool. However, for practical tools like FluoRender, it might better serve the developers' interests to distinguish real-world applications from simply related work. To prompt practical tool development, we would like to urge an impact measure designed for tools used in scholarly publications. A systematic categorization of tools for scientific research also provides a guide for scientists to search and choose tools in their research fields.

Surprises

In the process of FluoRender development, we often watch out for surprises, which really are bonuses for our work. Once we came across a Japanese computer builder and retailer's website, which listed FluoRender, among other bigname analysis and CAD tools, as one software package that their advanced workstation models could support. The thought that other business's sales are depending on our tool, albeit how insignificant the dependency may be, is a warm encouragement for our continued efforts.

CONCLUSION

The behind-the-scene stories of FluoRender have demonstrated the independent and interdependent development of a tool supported by visualization researchers and biologist users. FluoRender has experienced independent development by significant contributions to the visualization domain and through dedicated funding for such advances. At the same time, the development has been interdependent with the support from its users, for whom we adapted FluoRender to suit their needs and have driven many of the feature enhancements in FluoRender. In turn, biologist users' research workflows become dependent on our maturing tool. Who is the main body of this symbiotic development? There are always different answers with changing viewpoints.

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Fluorender, Our Sample Space For Visualization Development And Collaboration

FluoRender is a visualization and analysis system for fluorescence microscopy data, designed and engineered to meet the needs of researchers in biomedical sciences. The reasons that we chose FluoRender as an example of visualization development are as follows.

1. FluoRender has always been an academic project developed and maintained by a small and stable group. The authors of this article have been the main contributors to the project as visualization experts since its inception. It gives us an uninterrupted view and firsthand experience on developments focusing on consistent visualization tasks and goals.
2. FluoRender has been used in practice by biomedical researchers as both close collaborators and general users. It is evidenced in the over 100 biomedical publications that acknowledged the use of FluoRender, many from top academic journals for natural sciences. The FluoRender user community provides us a diverse population with fluency on visualization software, closeness of collaboration, domain-specific expertise, etc. spreading all cross the spectra. User engagement also varies over time, which can be influenced by many factors and felt by us over about a decade of the project's development.
3. FluoRender depends on government funding agencies' support. Over the years, FluoRender has received dedicated grants for its development and maintenance. This requires the establishment of FluoRender as an independent visualization tool with its own research merits as well as support and collaboration from its user community. Striking a balance between the two is essential to the survival of the project.

Therefore, we regard the viewpoints on visualization development and collaboration provided by the FluoRender project unique and effective.

A Summary of Our Interactions with Users

our interactions with FluoRender users may provide suggestions for other visualization system developers. We **reach out** to potential users, **listen to their needs**, and **exchange ideas**. To ensure **effective communication**, we pay attention to the ambiguity of **jargon** words, **openly discuss thoughts, let ideas flow, identify collaborators' talents, and be ready to help**. To **evaluate effectiveness, we observe user workflow** and **pay attention** to **user promotion** of visualization tools. Most importantly, a successful project needs mutual support from talented people. Table 1 lists the collaborators and users of FluoRender discussed in this article.

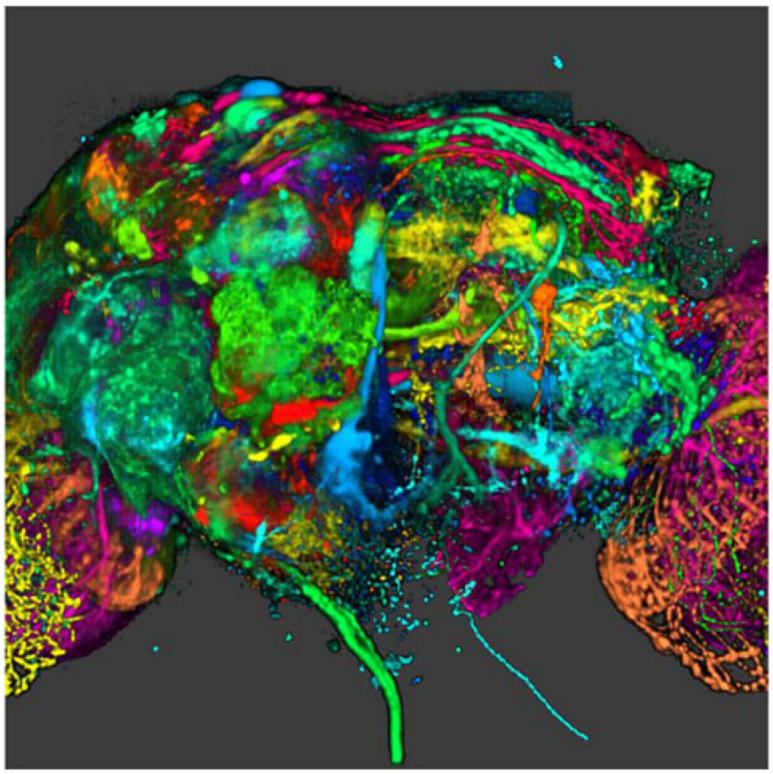

Figure 1.
A clonal composition of the Drosophila brain. The atlas is composed of 96 channels of neuronal structures, each colored differently. Ito lab used FluoRender to segment and render this Drosophila brain atlas.

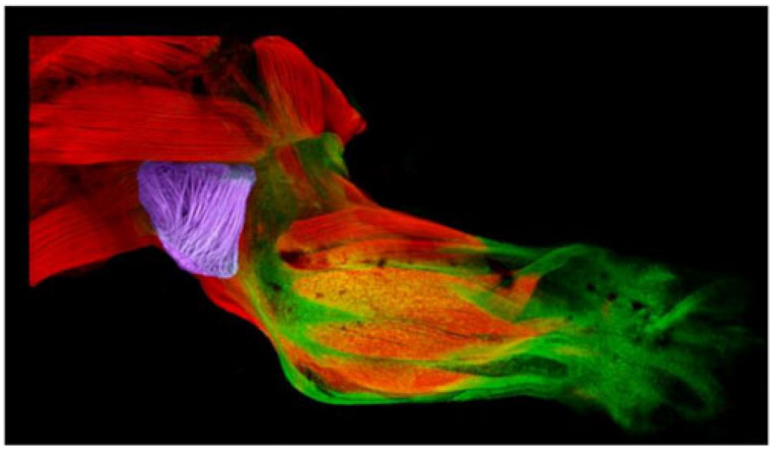

Figure 2.
FluoRender's brush tool was designed after the brush tool in Photoshop, allowing users to select biological structures in 3-D. The purple muscles were selected to identify the developmental anomaly.

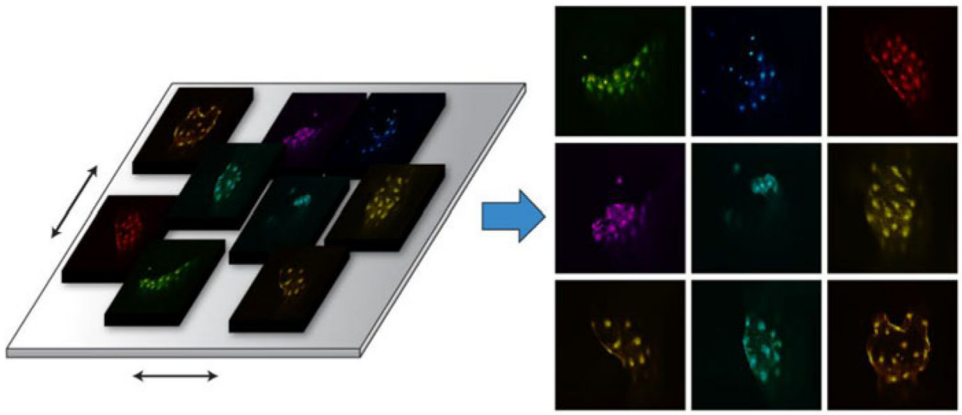

Figure 3.

Multiple samples are placed and scanned on a moving stage, which is designed for large biological samples by mosaicking. To help FluoRender users with their specialized use case, we separated a large scan into individual channels rather than stitching the mosaic.

Table 1.

Collaborators and users discussed.

Collaborator/User	Location	Needs
Chi-Bin Chien and lab	University of Utah	Volume visualization tool for confocal data in zebrafish research
Gabrielle Kardon and lab	University of Utah	Atlas building and image processing
Olympus Corporation	US regional branch of Japan-based company	Finely detailed visualization for advertisements
Holly Holman	University of Utah	Volume visualization tool for Olympus data Image analysis
Kei Ito and lab	University of Tokyo, Tokyo, Japan	Many-channel volume visualization
Anonymous lab	Chicago area, US	Volume visualization in zebrafish research
Prairie Technologies	Madison, WI, US	Volume visualization tools supporting specific microscopy formats
Microscopy Core Facility	University of Utah	Customizable tool for reading specific microscopy formats
Computer system builder	Japan	Selling computers to users of scientific computing and industrial design tools

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