Figure 1: This is a volume rendering of pressure and water applied to an ensemble comparison. The top two are $100\ m$ diameter asteroids while the bottom two images are $250\ m$. Within each diameter, the upper image burst on impact while the lower image bursts $5\ km$ above the surface.

Employing Color Theory to Visualize Volume-rendered Multivariate Ensembles of Asteroid Impact Simulations

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Abstract
We describe explorations and innovations developed to help scientists understand an ensemble of large scale simulations of asteroid impacts in the ocean. The simulations were run to help scientists determine the characteristics of asteroids that NASA should track, so that communities at risk from impact can be given advanced notice. Of relevance to the CHI community are **1)** hands-on workflow issues specific to exploring ensembles of large scientific data, **2)** innovations in exploring such data ensembles with color, and **3)** examples of multidisciplinary collaboration.

Author Keywords
scientific visualization; visualization design; volume rendering; ensemble visualization; colormaps.

ACM Classification Keywords
H.1.2 [User/Machine Systems]: Human Information Processing; H.5.2 [User Interfaces]: User Centered Design; I.3.m [computer Graphics]: Misc — Color

Introduction
In 2013 the Chelyabinsk meteor, perhaps only 20 meters across, exploded in a fireball above Russia, damaging over 7,200 buildings and prompting nearly 1,500 hospital visits [16]. While it may seem that asteroids entering earth's orbit are rare events, in fact an asteroid the size of an au-

tomobile enters earth's atmosphere on average once a year [9]. While these usually burn up before impacting the earth, they could impact the surface. One effect that is critical to understand is what would happen if an asteroid impacted the ocean [5]. Specifically, an impact in the ocean has complex effects as the kinetic energy of the asteroid is transferred to the water, potentially causing a tsunami that could affect coastal communities far away from the impact. Scientists interested in risk assessment are studying the characteristics of asteroids that could pose a threat.

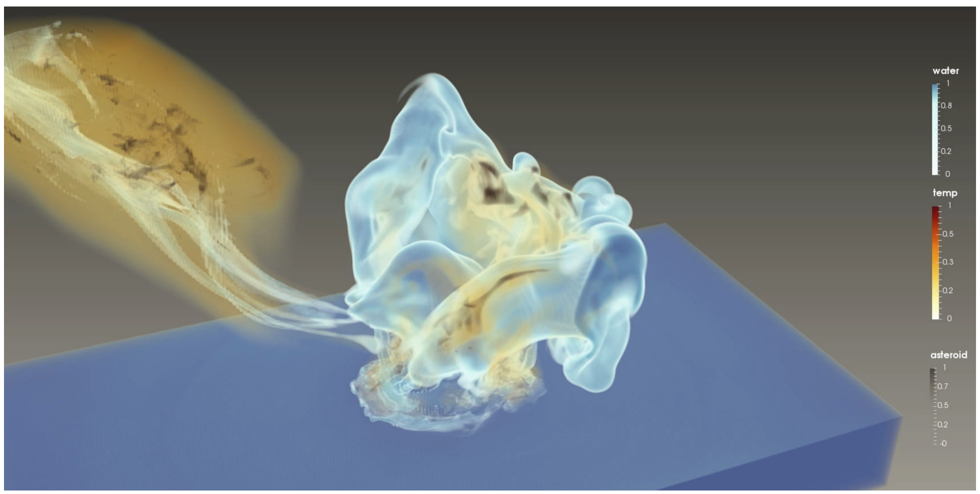


Figure 2: A volume rendering of the water, asteroid and temperature. Note the transparency of the temperature enables you to see the structure of the asteroid fragments, shown in dark brown within the ochre of the temperature. The trail to the left of water plume is a combination of water and asteroid particles exiting up the asteroid entry path via the vacuum created by its entry.

Galen Gisler, a Los Alamos National Laboratory scientist, is working with colleagues as part of NASA's Asteroid Threat Assessment Initiative. They are tasked with determining the smallest size of near-Earth Objects (NEO's) that should be tracked. This case study presents work contributed to the Second International Workshop on Asteroid Threat Assessment: Asteroid-generated Tsunami (AGT) and Associated Risk Assessment, held in August, 2016 [5].

Scientists study multivariate scientific questions by running a related group of simulations, known as an *ensemble*, to study various parameters that may affect the outcome of a simulation. In this example, the scientists varied the size of the asteroid, the angle of impact, and whether or not the asteroid exploded before impact, a phenomenon known as an *airburst*. Investigating the results of an ensemble can be a difficult task and is the topic of current research in scientific visualization [10]. In addition to the difficulties of dealing with single large simulations, ensembles introduce the complexity of comparing multiple individual large runs. We extend our previous work [13, 14] using color to improve the visual analysis of data from ocean models to asteroid impacts in deep ocean water. This case study details a novel, practical use of volume rendering, a well understood visualization technique with decades of research, development, and application [15, 17, 18]. We differentiated multiple variables and their structures in greater detail, allowing them to be visualized within a single visualization such as that seen in Figure 2. This facilitated understanding of the interaction between variables and allowed scientists greater access to the data and improved their ability to communicate across specialties on a science question of global concern.

We address complex problems like this with interdisciplinary teams to foster innovation in scientific discovery. The scientist, visualization specialists, high performance computing (HPC) specialists, and an artist collaborated to design ways of gaining deeper scientific insight from the simulation en-

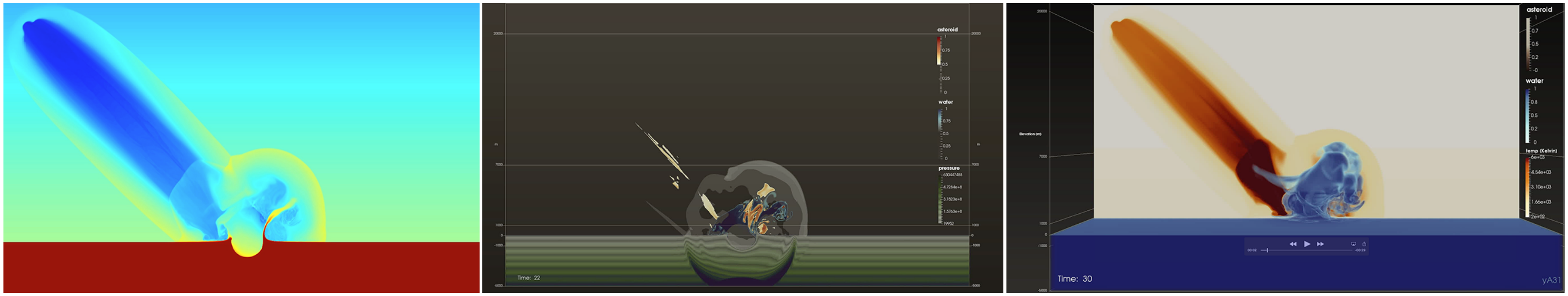


Figure 3: Left: original approach by scientist visualizing the single variable, pressure. The middle images pseudocolors the water, the asteroid and the pressure individually. The striated opacity transfer function accentuates the pressure wave information. The right image visualizes the temperature with the volume rendering of water. The combination of the two new images gives much greater detail on the variables of interest.

sembles. This collaboration works via an iterative process between all parties that looks at the critical science questions, the visualization and HPC challenges and capabilities, and develops solutions through this iterative process.

Exploration of the Problem (2D)

We began by considering the issue of 2D visualizations of an individual simulation and considered how color theory could enhance detail available within a visualization.

Prior to our collaboration, the asteroid scientist was visualizing the simulation's density variable as it provided a means of looking at the behavior of the entire system - how the asteroid, water, and resulting water vapor from the explosion behaved together in a broad sense. This is shown in the left image of Figure 3. Note the lack of detail in the water in particular. The scientist's single variable approach provided the scientist with a relatively simple visualization approach to understanding the data since only one variable was rendered and it involved a minimum amount of data manipulation. However, this approach did not allow the scientist to explore the full range of information in the simulation. A scientific simulation typically contains many variables that can be visualized, and the interaction of these variables can provide a more detailed view of the simulation.

The scientist was interested in studying density, pressure and temperature in order to get a more complete understanding of the physical interaction of the asteroid, water and kinetic energy.

In practice, scientists often visualize each variable separately as the interaction of variables can be visually confusing. While this may provide optimal clarity for an individual variable, context and the ability to compare across ensembles is difficult. In this work we balanced the need for clarity of each variable and the context and practicality of multiple variables in one image in order to provide scientists with means to assess the ensembles.

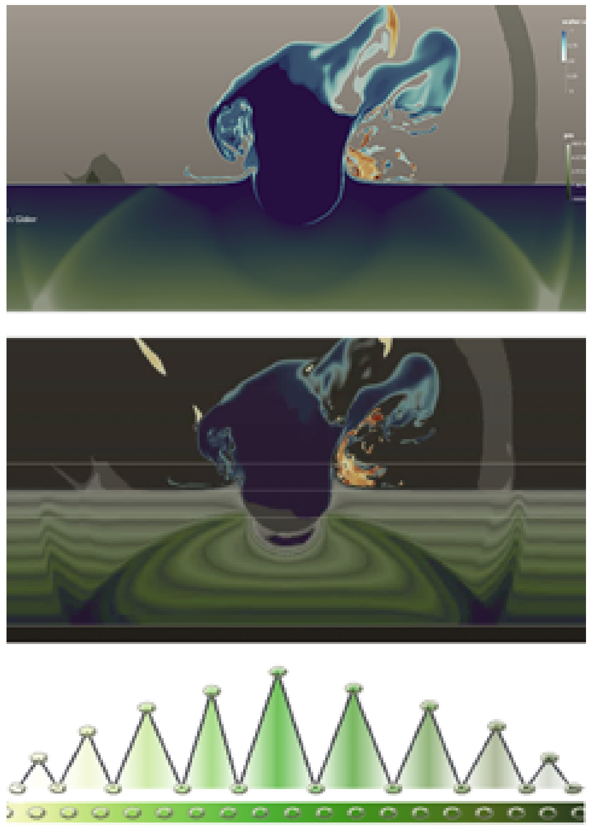


Figure 4: These before and after images illustrate the application (top) of the linear green colormap to pressure. Then the opacity transfer function (bottom) is applied to produce the middle image where the pressure waves in the water can be more clearly seen. This is the key to illustrating and communicating the pressure wave propagation, relevant to the question of tsunami production.

We experimented with color and opacity to determine whether or not we could expose features of value not visible in the univariate density rendering.

Univariate slices show the distribution of the asteroid, water and energy independently, requiring three images. Of great value is seeing the pressure waves in the water, the distribution of the temperature, and the physical structure of the water, juxtaposed with one another in a single image. Proper component registration can more easily build intuition and understanding of the underlying simulation [15] as demonstrated in Figure 3.

We also add value by applying color triads [1, 6] with ranges of opacity. The contrast provided by the color triads allows three variables within one simulation to be independently rendered and clearly distinguishable.

We addressed the ensemble analysis issue by simultaneously viewing four instances of the simulation. This allowed the scientist to compare several different sets of simulation parameters at the same time and repeatedly view them together. In practice, this allowed the scientists to understand how simulation parameters affected impact, water vapor, and wave propagation. This was first done with 2D slices of the data, and then the same technique was applied to 3D visualizations developed later like those in Figure 1.

Figure 4 demonstrates experiments with opacity. We were able to depict the structure of the pressure waves in the water with significantly more clarity by first applying a graduated opacity function: least and most pressure are more transparent. Detail was improved by removing stripes of varying opacity, the sawtooth pattern in the colormap. Coupling these two techniques created the stripe effect within the water that exposed further detail by visually creating isolines of pressure superimposed on the water.

The scientist had been using methods best suited for 2D simulations with radial symmetry, based on previous experiments [4] with 90 degree asteroid entries. 3D simulations

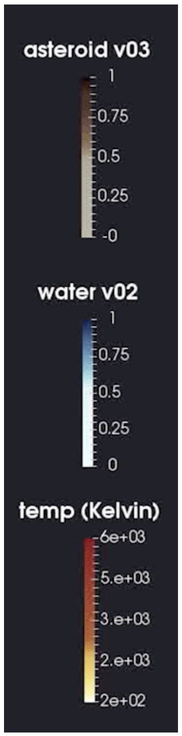


Figure 5: A closeup of the consistent colorscales used in many of these visualizations. Asteroid materal (top) is a linear brown, water is a linear blue and temperature is a linear orange.

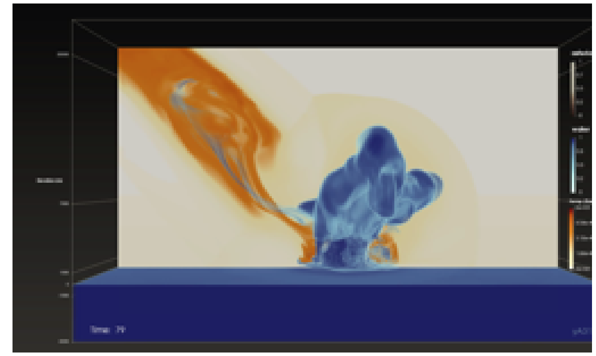
were necessary to study the more likely oblique entries because they are not radially symmetric. To study and develop intuition of the 3D entries and impacts, the team applied lessons from the 2D analysis.

Innovation of Solutions (3D)

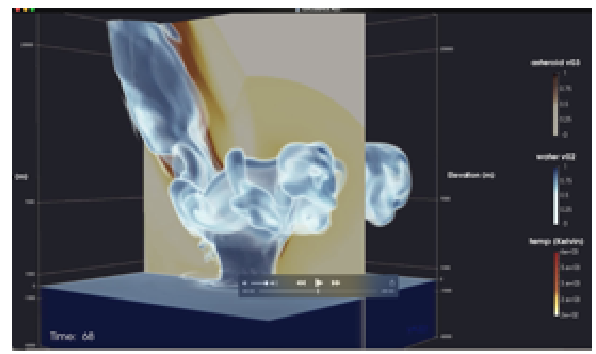
Volume rendering is extremely useful in the medical community to visualize 3D datasets from MRI and CT scans. Using transfer functions - mappings of value to color and opacity - scientists can emphasize different tissues in the data. Though complex transfer functions and associated interfaces have been developed to explore multivariate data [8], our work uses a production visualization tool, ParaView [2], with transfer function editors designed for univariate data sets. The tool is capable of interactively compositing multiple volume rendered pipelines into a single image.

Our team developed methods of sampling the large datasets and combining different volume renderings with complementary colormaps (Figure 5) to allow the scientist to view the full range of variables necessary to understand the simulation. Thus, the problem was studied in three dimensions, and the density of information was increased so that different variables could be viewed together, both within a single simulation, and across different simulations within the ensemble.

Visualizing the internal structures of a volume rendering requires precise tuning of the opacity levels, calibrated to the structures of interest. Enabling scientists to see multiple volumetric structures requires working closely with the scientist to understand the structures within each variable that are of interest and then balancing the opacity and hue in each simultaneously. Placing three time-varying physical structures in one time sequence means that some variables will obscure others. However, the context and reduced number of renderings of ensembles enable comparisons important to understanding the interaction of the physical states of the materials.



(a) Experiment 1



(b) Experiment 2

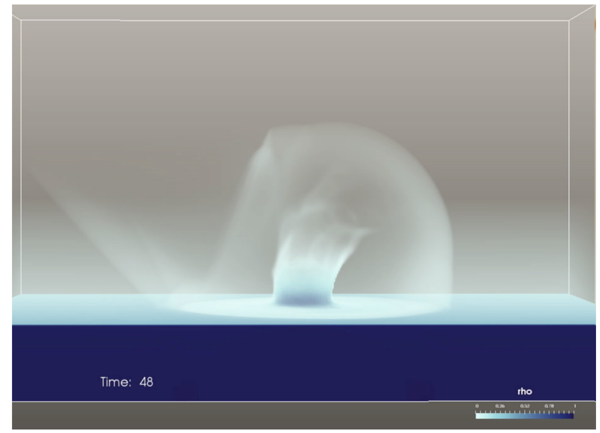
Figure 6: Various experiments were done to determine the visualizations most useful to the scientist. In Experiment 1, a slice is imposed on a 3D visualization of the asteroid and water materials and the pressure. A closeup view of the colorscales is given in Figure 5. In Experiment 2, the slice is rotated so the 3D water visualization can be seen.

Given there were three categories of variables we used color scales based on primary hues. We needed the variables to be distinct between types of visualization - volume renderings and slices. We also needed the hues to mix so opacity could be used to depict pressure while still indicating the water volume. We used saturation within the hue palette to identify the areas of focus. We identified the specific goal of each visualization and iterated on the color and encoding properties so that the visualization enabled a clear, quick understanding. Variables providing only context were colored in gray, using basic color theory principles [7] to isolate the areas of interest and direct attention.

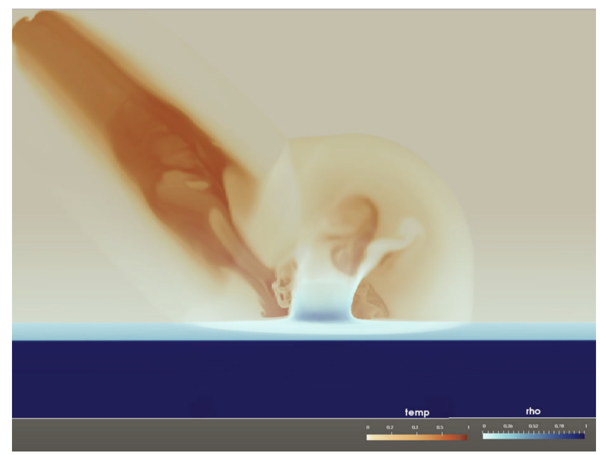
Critical to the development of practical solutions for this project were our regular all-hands meetings. The technical team needed feedback from the scientist on the scientifically significant details. As the technical team and the artist developed new visualization approaches, the scientist was able to see those visualization possibilities and provide input to further the iterative development process.

The 3D asteroid, water, and pressure volume rendering produced a holistic picture of the impacts. However, the scientists were more interested in a visualization that placed focus on water and temperature to more effectively illustrate the differences between ensemble runs. This is shown in Figure 3. Additionally, the distribution of heat and pressure in the air are of interest as both can cause significant damage, as seen in the Chelyabinsk asteroid explosion. They are rendered jointly in Figure 6, the temperature on a slice through the volume rendering of water. Figure 1 shows the combination of pressure and water, rendered as a slice and volume, respectively.

Qualitative volume renderings of water fraction like that seen in Figure 8 drove discussions among the scientists about the total amount of water- a known greenhouse gas-



(a) Volume rendering of rho (ρ)



(b) Volume rendering of ρplus temperature

Figure 7: Illustrating the visual impact of overlaying variables, the left image shows a volume rendering of pressure while the right shows the volume rendering with pressure and temperature.

Gisler sums up the value of our collaboration this way: "Images and animations like these give us insight in the physical processes in the simulation that are otherwise hard to extract from massive amounts of data."

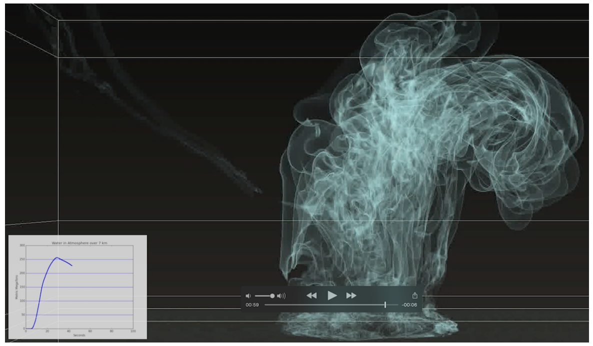


Figure 8: The qualitative volume visualization of water fraction helped to communicate and drive requirements for software to calculate the total amount of the potent greenhouse gas water ejected into the stratosphere.

being ejected into the stratosphere. The imagery drove the group to a realization that it would be relatively easy to quantify the total water making it to the stratosphere. Requirements discussions for software development were fast, given the volume representation as a discussion point. Software was developed that could be run on both saved data sets and in situ [3], during simulation run time, to quantitatively augment the qualitative volume rendering of water in the atmosphere. A resulting plot can be seen in the bottom corner of Figure 8.

These visualizations helped solidify and create consensus that deep ocean airburst asteroids are not a greater tsunami threat than ocean impact asteroids. The visualizations provide information and context as to the propagating wave potential created by the water crater as well as provide information about the structural properties of the pressure waves and water. One example of this is the two pressure waves visible on the incoming side of the asteroid. Prior to this visualization scientists were unaware of this multiple wave structure.

Conclusions

In this case study, we have demonstrated methods and practices for a color theory based approach to multivariate volume rendering using production visualization tools.

This work required multidisciplinary collaboration between widely diverse fields. Language and communication was key. While our team has worked together in the past, the challenges involved in working with the complexity of the science, the enormity of data, and the number of variables and time-varying ensembles required a close iterative interaction. The challenge involved developing a workflow that enabled us to get the data, process it, visualize it, and deliver scientifically relevant content, all in a practical, production workflow. This approach enabled more effective ensemble comparisons and allowed the scientific information to be more effectively communicated among the interested scientific community. Having the scientist in the loop kept the collaboration focused on visualizations that directly addressed and illustrated the important science questions. It also resulted in greater targeted detail in the ocean pressure and the pressure wave pattern visualizations. Additionally, the scientist drove the studies of water displacement and ejection into the stratosphere.

An award winning video [12] was also produced for Supercomputing 2016 using the visualizations produced in this collaboration to tell the science story of asteroid impact potential for tsunami generation and to highlight the High Performance Computing story of this work [11].

As stated by the project scientist, visualization is critical to facilitate understanding of the connections, drivers and implications of the linked experiments.

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