INFORMATION ABOUT PRINCIPAL INVESTIGATORS/PROJECT DIRECTORS

Submit only ONE copy of this form with your proposal. Attach it on top of the cover page of the copy of your proposal that bears the original signatures. Leave the back of the page blank. *Do not include this form with any of the other copies of your proposal, as this may compromise the confidentiality of the information.*

Please check the appropriate answers to each question for all principal investigator(s)/project director(s) listed on the cover page, using the same order in which they were listed there:

	Principal Investigator/ Project Director	First Additional PI/PD	Second Additional PI/PD	Third Additional PI/PD	Fourth Additional PI/PD
1. Is this person					
Female	☐	☐	☐	☐	☐
Male	☒	☐	☐	☐	☐
2. Is this person a					
U.S. Citizen	☒	☐	☐	☐	☐
Permanent Resident	☐	☐	☐	☐	☐
Other non-U.S. Citizen	☐	☐	☐	☐	☐
3. Which one of these categories best describes this person's ethnic/racial status? (If more than one category applies, use the category that most closely reflects the person's recognition in the community.)					
American Indian or Alaskan Native	☐	☐	☐	☐	☐
Asian	☐	☐	☐	☐	☐
Black, not of Hispanic Origin	☐	☐	☐	☐	☐
Hispanic	☐	☐	☐	☐	☐
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White, not of Hispanic Origin	☒	☐	☐	☐	☐
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No	☒	☐	☐	☐	☐
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ASIAN: A person having origins in any of the original peoples of East Asia, Southeast Asia or the Indian subcontinent. This area includes, for example, China, India, Indonesia, Japan, Korea and Vietnam.

BLACK, NOT OF HISPANIC ORIGIN: A person having origins in any of the black racial groups of Africa.

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Information from this form will be retained by Federal agencies as an integral part of their Privacy Act Systems of Records in accordance with the Privacy Act of 1974. These are confidential files accessible only to appropriate Federal agency personnel and will be treated as confidential to the extent permitted by law. Data submitted will be used in accordance with criteria established by the respective Federal agency for awarding grants for research and education, and in response to Public Law 99-383 and USC 1885c.

CERTIFICATION PAGE

Certification For Principal Investigators and Co-Principal Investigators

I certify to the best of my knowledge that:

(1) the statements herein (excluding scientific hypotheses and scientific opinions) are true and complete, and
(2) the text and graphics herein as well as any accompanying publications or other documents, unless otherwise indicated, are the original work of the signatories or individuals working under their supervision. I agree to accept responsibility for the scientific conduct of the project and to provide the required progress reports if an award is made as a result of this application.

I understand that the willful provision of false information or concealing a material fact in this proposal or any other communication submitted to NSF is a criminal offense (U.S. Code, Title 18, Section 1001.)

Name (Typed)	Signature	Date
PI/PD David Laidlaw	[signature]	9/11/96
Co-PI/PD		
Co-PI/PD		
Co-PI/PD		
Co-PI/PD		

Certification for Authorized Organizational Representative or Individual Applicant

By signing and submitting this proposal, the individual applicant or the authorized official of the applicant institution is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding Federal debt status, debarment and suspension, drug-free workplace, and lobbying activities (see below), as set forth in the *Grant Proposal Guide* (GPG), NSF 95-27. Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U.S. Code, Title 18, Section 1001).

In addition, if the applicant institution employs more than fifty persons, the authorized official of the applicant institution is certifying that the institution has implemented a written and enforced conflict of interest policy that is consistent with the provisions of *Grant Policy Manual* Section 510; that to the best of his/her knowledge, all financial disclosures required by that conflict of interest policy have been made; and that all identified conflicts of interest will have been satisfactorily managed, reduced or eliminated prior to the institution's expenditure of any funds under the award, in accordance with he institution's conflict of interest policy. Conflicts which cannot be satisfactorily managed, reduced or eliminated must be disclosed to NSF.

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Is the organization delinquent on any Federal debt?	Yes O	No X
Is the organization or its principals presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency?	Yes O	No X

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This certification is required for an award of a Federal contract, grant, or cooperative agreement exceeding $100,000 and for an award of a Federal loan or a commitment providing for the United States to insure or guarantee a loan exceeding $150,000.

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The undersigned certifies, to the best of his or her knowledge and belief, that:

(1) No federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

(2) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with this Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, "Disclosure of Lobbying Activities," in accordance with its instructions.

(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

AUTHORIZED ORGANIZATIONAL REPRESENTATIVE NAME/TITLE (TYPED)		SIGNATURE	DATE
Richard P. Seligman, Director Sponsored Research		[signature]	9-12-96
TELEPHONE NUMBER	ELECTRONIC MAIL ADDRESS		FAX NUMBER
818/395-6357	office@sponsres.caltech.edu		818/795-4571

PROJECT SUMMARY

The Project Summary should include a statement of objectives, methods to be employed, and the significance of the proposed activity to the advancement of knowledge or education. Avoid use of first person to complete this summary. DO NOT EXCEED ONE PAGE. (Some Programs may impose more stringent limits.)

Computer Graphics Tools for Understanding Tensor-Valued Volume Data: A Painting Metaphor

This proposal describes a multi-disciplinary research project to discover new computer graphics tools for understanding vector- and second-order tensor-valued volume data. The efficacy of the tools will be evaluated by the extent to which they generate insight into several specific physical phenomena: fully-developed turbulent flow, the progression of disease in a mouse analogue of multiple sclerosis, and the neonatal development of the mouse brain. The application of the new techniques and collaboration with researchers in other fields provides us with a unique opportunity to validate the techniques and ensure that they are responsive in addressing the scientific problems.

The techniques will be developed using a painting metaphor. For centuries artists have used a divide-and-conquer approach to creating paintings, representing different aspects of a scene in different layers of paint. In addition, artists use brush strokes, with their many characteristics of texture, size, shape, color, and opacity, to represent important features of a scene on a canvas, depicting the essence of the scene and eliminating unnecessary detail. Both techniques, and the collective artistic experience in using them, can be applied to computer g. aphics in the context of displaying volume data. Techniques for understanding vector-valued and tensor-valued volume data stand to benefit particularly, because volumes contain so much information and because tensor and vector values have many relevant, interdependent aspects. Existing techniques are limited in their ability to abstract the data effectively and to display the many relevant aspects of the data simultaneously, but the new techniques will address both of these problems. As a result, they will be more effective in generating insight into the physical phenomena measured as well as in communicating the insig! . Because the techniques will be developed with application to three specific problems in two disciplines, they are likely to have broader application.

A visual-programming paradigm will be used to experiment with techniques. It will be built upon a commercially available interactive environment (AVS) and will speed development. Because the environment is readily accessible, other computer graphics researchers and scientists in other disciplines will be able to quickly develop techniques that build upon this work and that apply not only to biology and fluid mechanics, but also to other domains.

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Appendix Items:

*Proposers may select any numbering mechanism for the proposal. Complete both columns only if the proposal is numbered consecutively.

Project Description

Computer Graphics Tools for Understanding Tensor-Valued Volume Data: A Painting Metaphor

Visualization has always contributed to endeavors of art, science, and engineering. By tapping into the remarkable capabilities of the human brain to grasp complexity, it has helped practitioners in all three endeavors achieve a better understanding of aesthetic, natural, and technological objects, phenomena, and processes. In science and engineering, where adequate visualization has been an important part of the creative process, it has yielded new insights into complex phenomena and catalyzed better descriptions and predictive models. Indeed, substantive progress in many complex fields has often awaited the development of adequate quantitative imaging and visualization methods.

1 Goal: Insight into Physical Phenomena

The ultimate goal of any scientific computation technique is to generate insight into and predictions about physical phenomena. The research effort described here is focused with this philosophy in mind and strives to advance present state-of-the-art, quantitative, multi-dimensional imaging and computer graphics technology for the investigation of physical phenomena, with an emphasis on the study of fully-developed turbulent flows and neurobiological development utilizing multi-dimensional imaging techniques.

The common thread connecting the disciplines is a desire to gain this insight through the display of experimental measurements (see Figure 1). We expect novel contributions in interactive computer graphics techniques for displaying multi-dimensional data that will take full advantage of the capabilities of the human visual system, in measurement methodologies of both turbulence and developing neurobiological systems, and in insight into the underlying physical systems.

1.1 Goal: Understanding Multi-Dimensional Imaging Data

Understanding vector-valued and second-order tensor-valued volume measurements is a key step in developing insight into the physical phenomena that they represent. Measurement capabilities, which are now available for both biological systems and for turbulent mixing, are outstripping our ability to visualize and understand the data acquired. Not only is the quantity of the collected data growing rapidly with 100 mega-voxel datasets routinely acquired on our MRI microscope, but the complexity of the measurement at each voxel is growing as well. A measured or calculated vector- or tensor-valued quantity at each point in a region of space presents a visualization challenge because the interpretation of the quantity is not equivalent to the interpretation of a collection of scalar values.

1.2 Problem: Complex Data Primitives

Vector- and tensor-valued fields are a challenge to visualize because the value at each point in a dataset has a complicated interpretation. Many visualization techniques, e.g., isosurfaces [Lorensen and Cline, 1987] and volume rendering [Drebin et al., 1988], have focused on understanding scalar-valued measurements. Because data can often be decomposed into scalars, these techniques have served scientists well. They are somewhat limited, however, at showing the relationship between different components of the data. Consider the decomposition of a velocity field into scalar components. While the individual scalars can be viewed independently, their interpretation as a velocity requires that they be understood collectively. With

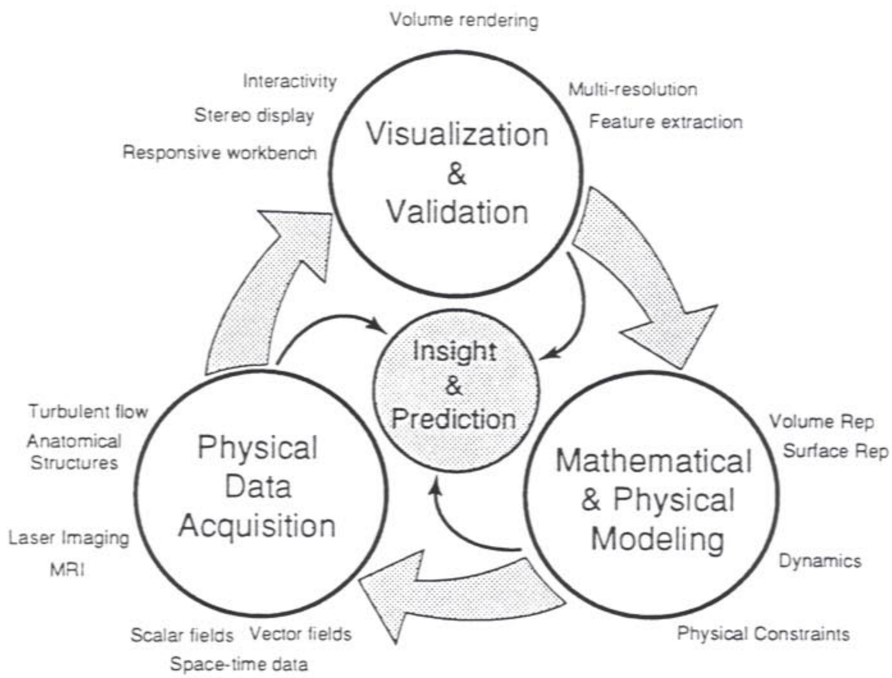

Figure 1: The central goal of any scientific computation technique is to facilitate insight into and predictions about physical phenomena. Through the cycle of data acquisition, visualization, and modeling we expect to not only explore and validate the efficacy of new visualization tools, but also to answer questions about turbulent flow and developmental neurobiology.

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experience and training, this understanding can be intuited from the scalar views, but techniques that show the components together are frequently more intuitive, and are an improvement on the scalar techniques.

A velocity field can be represented with arrows, but a symmetric, second-order tensor field provides a more complex example. Over three-space a tensor can be represented by a 3x3 symmetric matrix. Therefore, the tensor value at each point can be represented by six scalar values, which can be viewed either independently or in subsets. However, additional insight and comprehension comes from a more holistic perspective of the relationships between the six scalar values.

With measured data each measurement has some uncertainty. On a graph, error bars can represent this uncertainty, and can aid in understanding. Similarly, with the volume data, the uncertainty becomes another component of the complex voxel measurement yet another value to incorporate into an image, perhaps through mapping it onto the fuzziness or diameter of brush strokes.

1.3 Problem: Information Overload

The information contained in a tensor-valued volume dataset of a complex biological system cannot, in general, all be encoded into an image. The measurements typically vary throughout the subject, and are defined within a three-dimensional region. They can be projected onto an image, but each point in the image then represents a one-dimensional portion of the dataset. To create meaningful images, choices must be made to abstract the data and present the "important" parts.

1.4 Method: Computer Graphics Tools with a Painting Metaphor

In section 2 we propose an interactive environment that addresses the two difficulties in creating images of tensor fields: information overload and complex data primitives. The novel aspects of this environment are two techniques derived metaphorically from painting

The first technique involves building up an image as a series of "layers," providing a way to organize an abstraction of the underlying data. Each layer presents one aspect of the data, with more important upper layers possibly obscuring less important lower layers.

The second technique is modeled on the use of paint brush strokes to represent aspects of a scene in a painting. Aspects of the data are mapped onto characteristics of "brush strokes." These stroke characteristics of color, orientation, shape, texture, and opacity have the potential to effectively represent the complexity of tensor and vector values. In contrast with the ability of brush strokes to represent many detailed aspects of single data values, they can also be used to give an overall impression of regions of data, thus reducing the representation of the many measurements in a region to a single stroke.

The system we envision and more details of the painting metaphor are described in Section 2.

1.5 Evaluation: Insight into Physical Phenomena in Multiple Disciplines

Understanding physical phenomena through the use of computer graphics is inherently multi-disciplinary and requires expertise not only in traditionally graphics-related domains, such as computational geometry, graphic design, user-interaction, and functional analysis, but also in the scientific disciplines from which problems are derived. Close coupling of the development of new visualization techniques to their application in other disciplines is critical to the utility and longevity of these techniques.

We propose to evaluate the efficacy of the new computer graphics techniques through their effectiveness in generating insight into and understanding of three phenomena: fully-developed turbulent flow, the progression of a disease similar to multiple sclerosis in a mouse, and the neonatal development of the mouse brain. The evaluation projects we plan are described in more detail in Section 3.

We will work with sampled measurements of continuous fields, where data (1) are acquired over both two- and three-dimensional spatial domains, (2) can be time-dependent, and (3) may be scalar, vector, or tensor valued. We will utilize two existing data-acquisition facilities at Caltech: laser-imaging apparatus for measuring turbulent mixing and a Magnetic Resonance Imaging (MRI) microscope, ultimately capable of 4 μm resolution, for measuring developing biological systems non-invasively. Figure 2 shows examples of data collected with these facilities.

2 Vector and Tensor Field Visualization

In this multi-disciplinary context, we propose to explore new visualization techniques for investigating vector-valued and tensor-valued fields acquired as measurements of physical phenomena. Our approach will use a commercial interactive visualization programming environment, AVS, together with a set of tools developed within that environment to implement a painting metaphor. We will also build upon the existing visualization tools available in AVS.

2.1 Painting Techniques

Our new computer graphics tools will be based on the application of two concepts used by artists in oil painting: paint layers and brush strokes.

2.1.1 Paint Layers

Painters commonly build up an image through successive application of layers of paint. These layers are sometimes arranged by lighting, with dark, broad strokes put down first, and lighter, smaller highlights painted successively. Layers can also be used to separate different objects in a scene: the background in one layer, and different foreground objects in other layers. Cel animators have also used this concept to create multi-layer animations with breathtaking complexity, and computer graphics production has borrowed the idea as a speedup because only modified layers need be recalculated as changes are made.

This layered approach is akin to the divide-and-conquer strategy that has been applied so successfully in many areas of computer science, and it holds promise as a tool for interactively creating visualizations of scientific data. By creating individual layers that represent different aspects of a dataset, and then combining them, we can show many aspects of the data in the same image while retaining control over how each layer is created. Using a computer the layers can easily be modified interactively and recombined in many ways, giving far more creative freedom to explore relationships in the data than an artist might have to develop an oil painting.

2.1.2 Brush Strokes

Brush strokes are complex and have many characteristics that can be used to represent aspects of data. These characteristics can be used to represent a scene at a very detailed level, with a stroke representing minute details, or to abstract the character of a scene giving the impression of the geometry and lighting that they are representing. Small blotches might represent leaves on a tree; long, broad, wavy brush strokes the shape and energy of the waves on a lake; or seemingly unrelated spots of color the flowers in a garden. Some of the brush stroke characteristics include size, shape, texture, blending, color, placement, and orientation, and they can all be utilized to represent different aspects of data.

The concepts of data representation and abstraction are also used in other artistic domains, including graphic design, illustration, and sketching, and that experience can also be drawn upon in this work. Pen-and-ink line widths, cross hatching, and patterning are examples from illustration, but many others exist.

2.2 Advantages of the Metaphor

There are a number of aspects of the painting metaphor that hold promise for effectively visualizing large datasets of complex primitives. Figure 3, a two-layer visualization of vector-valued fluid flow over an airfoil, shows preliminary work that illustrates some of these aspects. This example shows the basic concepts of brush strokes and layers in an application to two-dimensional data, but the techniques developed will also apply to three-dimensional data, where the parameters of the brush strokes will not only encode the data characteristics, but will also encode information about the placement of different portions of the data in three-space and be placed to effectively illustrate the volumetric nature of the data.

2.2.1 Many Simultaneously Visible Brush-Stroke Parameters

The many characteristics of a brush stroke, including color, texture, opacity, shape, size, and orientation, permit many aspects of underlying data to be displayed simultaneously. Vector-valued or tensor-valued data, then, can be represented within an image, and the relationship between their component parts more easily illustrated. In Figure 3 the orientation of texture in each brush stroke in the lower, blue, layer represents the direction of the flow, and the color its magnitude. Brush strokes are capable of representing much more information than this simple example shows. Their size could be used, the shapes could be curved to represent derivative information, or more complex textures could represent other aspects.

2.2.2 Freedom to Place Brush Strokes

In addition to the appearance attributes of brush strokes, their location can impact an image as well. Careless placement, for example on a regular grid, can introduce the appearance of structure where there is none. Careful placement, on the other hand, can focus a visualization on those regions where the behavior is "interesting." The placement can be implemented through static rules governing brush stroke placement or through computational optimization [Turk and Banks, 1996]. In visualizing the velocity field in Figure 3, the bright, highly-visible strokes of the top layer are present in regions where the flow has a particularly high curvature.

2.2.3 Data Abstraction

As with brush strokes in a painting, virtual brush strokes can abstractly represent information. For example, one paint brush stroke might represent many leaves on a tree through its texture; similarly, the texture of a virtual stroke might represent characteristics of several voxels. Vector and tensor fields contain much information, usually too much to display in a single image, and this abstraction can help to manage that complexity. In Figure 3 the bottom layer effectively represents the flow field even though there is only one stroke for many measurements because the field is relatively constant where those strokes remain visible. Where the field varies more quickly the more-refined top layer obscures the coarse strokes.

2.2.4 From Iconic to Continuous Representations of Data

Through the use of different brush strokes and placement, painterly techniques can span the continuum from iconic to continuous representations of data. At the iconic end, a sparse sampling of "rubber stamp" arrow-shaped strokes can represent a vector field; at the continuous end, small overlapping soft-edged textureless strokes blend together to represent the same data type. Stroke size, spacing, and transparency can all impact this aspect of an image.

Iconic techniques can be very flexible, with icons ranging in complexity from arrows or streamlines whose length and/or direction represent a velocity, to stylized human faces, where each feature of the face represents an aspect of the data. We can draw upon these concepts in developing brush strokes.

2.2.5 Rich Space of Visualizations

The space of possible visualizations given the use of multiple layers and brush strokes with many parameters is large and varied, and contains useful techniques for many applications. Searching this space will allow for discovery of single effective techniques, as well as for exploration of the measured data and the phenomena they represent through families of techniques. Changing the character of a visualization, e.g., alternative layer organizations, can effect better understanding of a dataset, as can more subtle changes, e.g., brush shape adjustments.

The bulk of this project is exploratory, and the exploration process will happen at several levels. At the first level we will search the space of visualizations, experimenting with different mappings from data values to brush appearance parameters and placement. At the second level we will explore datasets with the discovered techniques. This exploration will help us understand the data, help evaluate the techniques, and help suggest new regions of the space of visualizations to search. Finally, at the third level, we will seek insight into physical phenomena using what we learn both to understand the phenomena and also to suggest new measurements to make and new visualization techniques to try.

A potential peril of sampling this vast space is that some techniques can be misleading, either by hiding an important feature in a dataset or by falsely showing a feature that does not exist. Our evaluation process

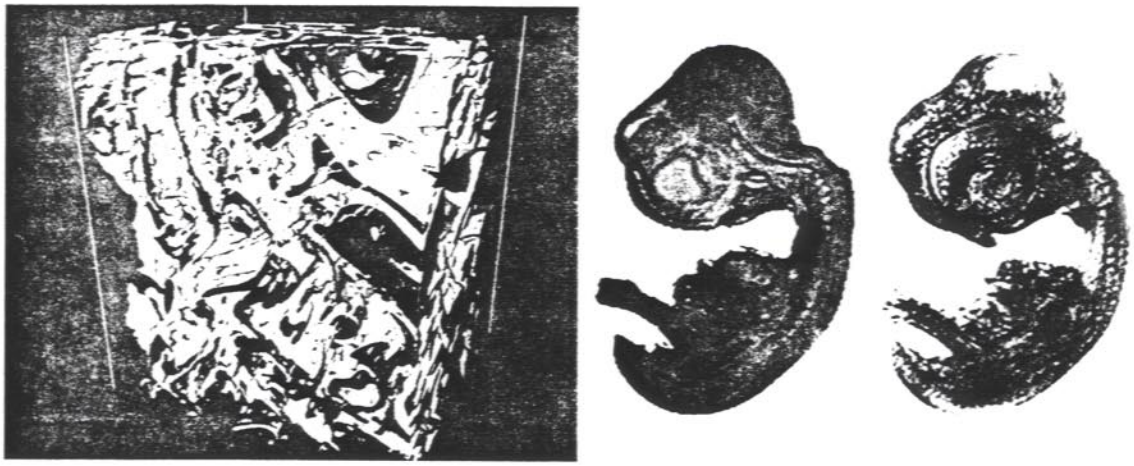

Figure 2:

(a) Jet-fluid concentration space-time slice of an isosurface generated by turbulent mixing, computed from multi-dimensional laser-imaging measurements in the far field ($z/d \approx 300$) of a liquid-phase turbulent jet. Time is color-encoded and mapped onto a spatial dimension.

(b) Two volume renderings of Magnetic Resonance Imaging (MRI) data of a fixed seventh-day chick embryo. The images show a wealth of internal and external anatomical detail; somites, telencephalic hemispheres, and condensing of digits in the limbs are especially apparent. The embryo is 15mm high.

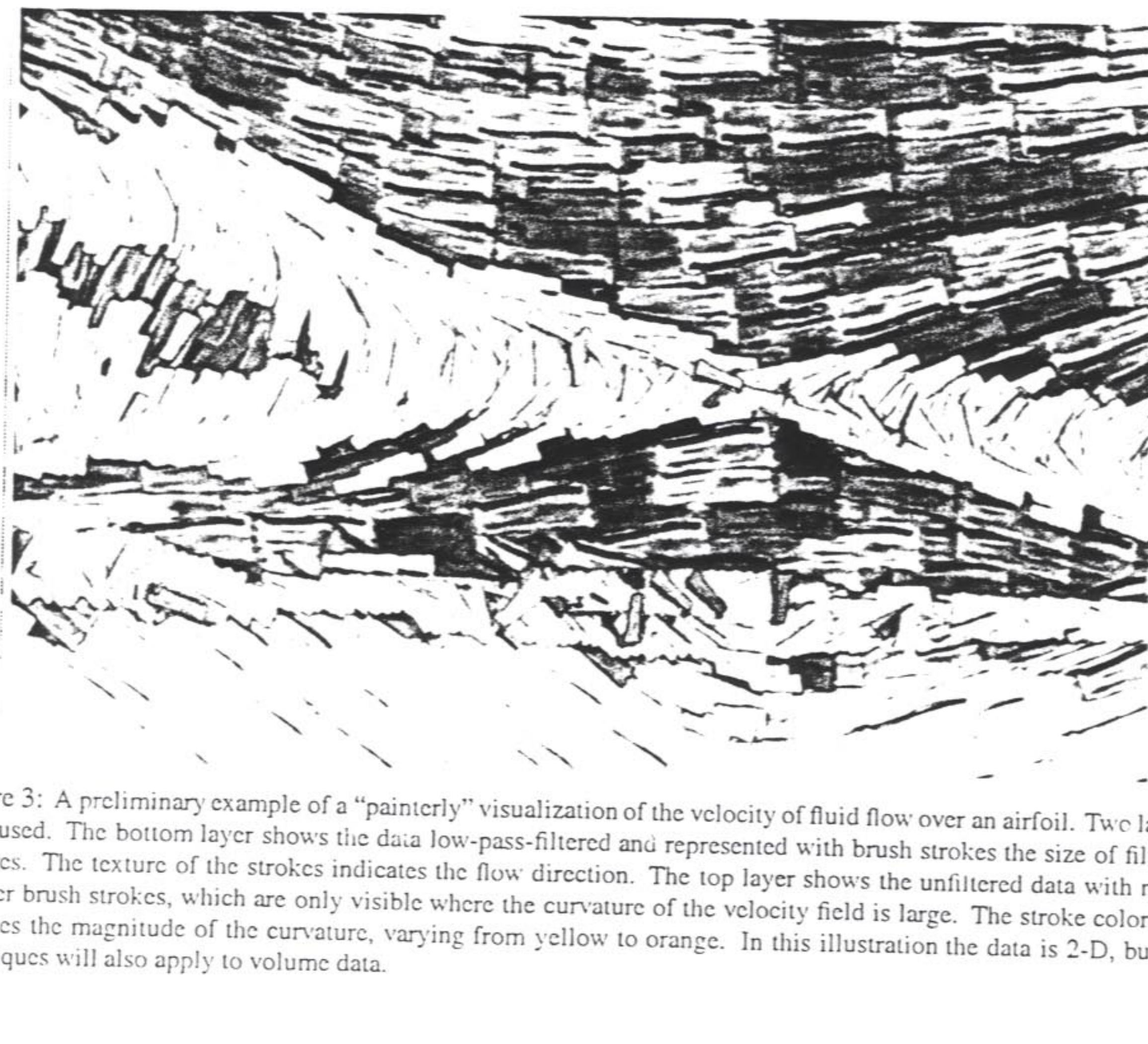

Figure 3: A preliminary example of a "painterly" visualization of the velocity of fluid flow over an airfoil. Two layers were used. The bottom layer shows the data low-pass-filtered and represented with brush strokes the size of filtered features. The texture of the strokes indicates the flow direction. The top layer shows the unfiltered data with much smaller brush strokes, which are only visible where the curvature of the velocity field is large. The stroke color also encodes the magnitude of the curvature, varying from yellow to orange. In this illustration the data is 2-D, but the techniques will also apply to volume data.

and familiarity with examples of misleading techniques will help us to be vigilant in maintaining data integrity during this exploration process.

2.2.6 Artistic Experience

There are many artistic styles that give hints for navigating this space of visualization possibilities, and each embodies a set of stylistic variations for abstracting a scene and representing portions of it with brush strokes. This historical record, and techniques from how-to-paint books [Katchen, 1990] [Kreutz, 1986], give a wealth of ideas to draw from for developing suitable visualization techniques.

2.3 An Interactive Visualization Environment Using AVS

An interactive environment that allows for quick experimentation will facilitate rapid convergence on effective visualization strategies. We will use AVS [Upson et al., 1989] as a computational framework for creating and modifying our techniques. AVS is a visual-programming environment in which computational modules are connected to define the flow of data. Figure 4 shows an example of an AVS network of modules. Each module performs a computation on its input data elements and creates new output data elements that flow along connecting paths. Possible data elements include volume data sets, images, brush shapes, and colormaps. Each module has a set of parameters that can be interactively modified to change a visualization. The modules connections can also be interactively modified to change the character or number of layers, the scheme for creating a particular layer, or the processing done to an intermediate data element before it is used to create a layer. Finally, modules can implement existing visualization techniques like surface rendering or volume rendering and create intermediate results that influence a layer.

AVS supplies the interaction tools in an environment that requires no programming, and so our focus can be on experimentation with visualization strategies and evaluation of their effectiveness, and not on development of user interface software.

2.4 Incorporating Existing Visualization Techniques

In addition to providing user interface tools, AVS provides a set of visualization modules, and we can extend its repertoire with tools of our own. These tools can serve as building blocks for creating layers; some of the most promising techniques we plan to incorporate are:

Surface Rendering A traditionally computer-rendered image of a surface might be used as the color for brush strokes representing a vector field on the surface. The lighting and shading, then, would carry over to the brush strokes and give the paint layer the appearance of a three-dimensional surface.

Tissue Classification The identification of regions where particular materials lie within a sampled volume dataset can be used to influence a visualization. Different colors can be applied to different materials, boundaries between materials used to define surfaces or edges where brush strokes might be placed, or particular materials can be removed to allow others to become visible. We have developed a set of classification techniques that are particularly effective for visualization because they model the underlying geometry and avoid artifacts at material boundaries. [Laidlaw, 1995] [Ghosh et al., 1995]

Isosurface Calculation The geometric locus of points where a scalar field over three-space takes on a constant value defines a surface. Figure 2a shows an example of such a rendered isosurface. Isosurfaces can have a physical interpretation, and their location could be used to locate brush strokes or to create a rendered image, as above, for coloring them. An isosurface of classified data can represent the physical boundaries between materials.

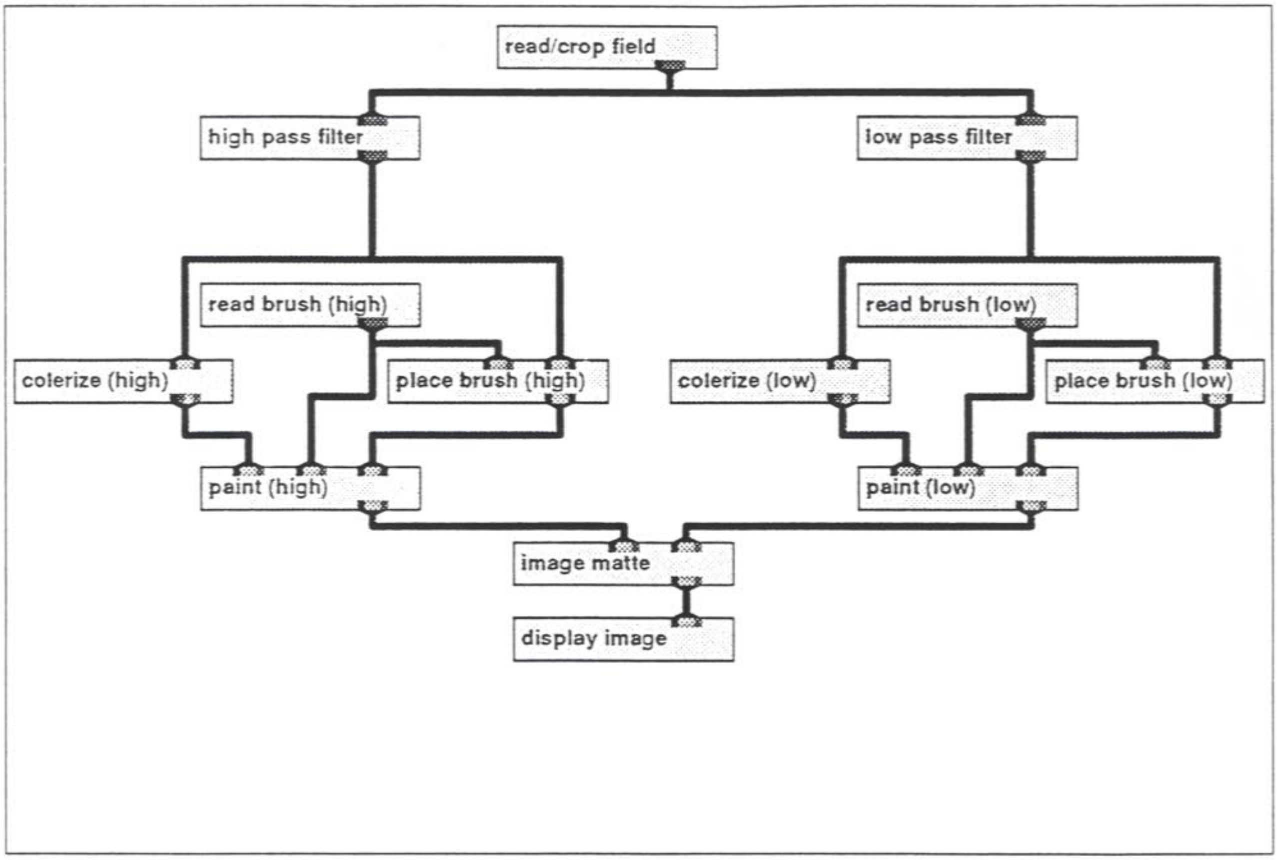

Figure 4: An AVS network of computational modules that implements the visualization technique shown in Figure 3. Each box represents a computatoin, with datasets, images, sets of brush strokes, and other data flowing top to bottom along the connecting lines. For this visualization a slice of velocity data is input at the top, filtered into two representations, one with only low-frequency information, and the other with both low- and high-frequency information. Each version is painted onto a layer and the layers composited together.

Volume Rendering Because volume rendering integrates through a volume and does not represent surfaces only, it can show both the internal and external structure of an object. A set of such images that encode information about volume scalar data might serve as input to control brush parameters that then represent the complex relationship among the scalars. Volume rendered images of classified data can be particularly useful since each material can be represented in the resulting image with a unique type of brush stroke.

2.5 Related Computer Graphics Work

[Haeberli, 1990] was the first to experiment with painterly effects in computer graphics, and his work is an inspiration to us. [Meier, 1996] extended that work for animation more recently, motivating the concept of layers and brush stroke attributes well and describing a useful set of tricks for creating effective imagery. Both of these efforts were aimed toward creating art, however, and not toward visualizing scientific data. Along similar lines, [Winkenbach and Salesin, 1996], [Winkenbach and Salesin, 1994] and [Salisbury et al., 1994] address the use of computer graphics to create pen and ink illustrations for artistic purposes and motivate the concept of data abstraction, which their illustrations implement so well. Finally, the classic [Tufte, 1983] presents many ideas for displaying data graphically.

[Hesselink et al., 1994] gives an overview of research issues in visualization of vector and tensor fields. While there are several techniques that apply to some problems, particularly for vector fields, the underlying data are still difficult to comprehend and often poorly understood, particularly for tensor fields. The authors suggest that "feature-based" techniques, i.e., techniques that extract and iconically display important aspects of data, are the most promising research areas, and our approach will generate techniques that are feature based.

[Delmarcelle, 1994] reviews specific techniques for tensor-field visualization [Haber and McNabb, 1990] [Haber, 1990] [Dickinson, 1989] and develops one of the most effective tensor-field visualization techniques [Delmarcelle and Hesselink, 1993]. Sections of [Pickover and Tewksbury, 1994] and [Gallagher, 1995] also give good reviews of techniques.

The techniques developed thus far have applications, but only very sparsely sample the range of possibilities for the order of the displayed data, the domain of the displayed data, and the iconic-to-continuous range of representation. Our techniques will simultaneously display more information, and thus give a more intuitive holistic understanding of the displayed data.

3 Evaluation

The evaluation strategy will focus on the application of a variety of new visualization techniques to problems from fluid mechanics and biology. In each case, measurements of physical systems will provide test cases for the techniques, and the generation of insight into the measurement and systems will determine the applicability of the techniques and guide the search for new ones. The measurements will be carried out using an MR microscope and a facility for laser imaging of fluids. Other Biological Imaging Center facilities for multi-spectral light microscopy will also be available for data acquisition.

3.1 Neonatal Mouse Neural Development

A magnetic resonance micro-imaging system in the Caltech Biological Imaging Center is currently operational and providing vector-valued *in vivo* MRI data of biological subjects including mice, frog embryos, and chick embryos. Figure 2b shows an example. A series of neonatal mouse embryos at various stages of development have been imaged. Each dataset in this atlas measures a vector field over a box containing the mouse, with from four to sixteen elements in the vector. We plan to experiment with methods of abstracting these data vector fields so that they are meaningful and can be compared to one another to better show developmental changes. This work is in collaboration with Dr. Scott Fraser, the director of the Biological Imaging Center, and his colleagues, including Dr. Russell Jacobs.

3.2 An Analog of Multiple Sclerosis in Mice

Multiple sclerosis (MS) is a demyelinating autoimmune disease some aspects of which have been better understood through the study of similar diseases in animals. A recently developed transgenic mouse [Goverman et al., 1994] spontaneously develops experimental allergic encephalomyelitis (EAE), a disease whose pathology mimics that of MS in humans. Because every animal develops the disease spontaneously, it is possible to study the progression before symptoms develop, and Dr. Eric Ahrens is working at Caltech in conjunction with Dr. Carol Readhead of Cedars/Sinai Hospital to use MR micro-imaging to do so. We conjecture that as the disease develops the diffusion characteristics in affected neural tissue will change. The diffusion characteristics are represented by a second-order tensor field, and the tensor field will provide rich information about the tissues within each voxel and their geometric relationships. We plan to collect MR images with a new protocol that measures this tensor value, visualize changes as the disease progresses, and confirm those changes with histological studies. Ultimately, the results will help us evaluate the visualization techniques in addition to better understanding the disease.

3.2.1 Diffusion Tensor Imaging

As part of the EAE mouse project we will develop a new MR imaging technique for measuring the diffusion tensor field within an animal. The diffusion tensor field can be calculated from a set of scalar MR images. The intensities in each image are functionally dependent on the diffusion tensor field and the effects of strong magnetic gradients [Mattiello et al., 1994]. A Levenberg-Marquardt non-linear solver [Press et al., 1992] will extract the tensor value for each voxel.

3.3 Fully-Developed Turbulent Mixing

A facility for capturing images of fluorescent dyes in turbulently mixing fluids is also operational and capable of collecting temporally-varying concentration measurements. Figure 2a shows an example. This raw data is scalar, but can be used to derive higher-order data including vector-valued velocities [Tokumaru and Dimotakis, 1995]. Through visualizing these measurements, attempting to model the underlying phenomenon, and returning to acquire further measurements we expect to gain new insight into the behavior and mechanisms of turbulent mixing. This work will be performed collaboratively with Dr. Paul Dimotakis and members of his research team.

4 Work Plan

The proposed timeline for this work is shown in Figure 5. There are three phases to the work proposed. During the first, or startup, phase we will create the computational framework and gather data for testing purposes. During the second phase we will extend the computational capabilities and create a library of visualization strategies. The strategies will be applied and evaluated during the third phase.

Major milestones approximately each six months will allow overall tracking of the project, and tracking the progress toward each of these major milestones can be easily done within each phase.

4.1 Phase 1: Startup

Three parallel efforts comprise the first phase, which is expected to take about 6 months.

4.1.1 Computational Framework

First, we will develop a computer testbed that allow us to build layered visualizations with brush strokes. The framework will be developed within AVS, and a module produced that "brushes" strokes onto a computational "canvas" or image. AVS has some facilities for layering images, but they may need to be extended. Initially the brush strokes in the testbed will be able to change orientation, size, color, and opacity based on functions of the underlying data.

4.1.2 Diffusion MR Imaging

In parallel we will develop a magnetic resonance imaging technique for collecting tensor-valued data of biological systems. We will also collect data of several biological systems as a basis for creating and experimenting with visualization algorithms in the second phase of the project.

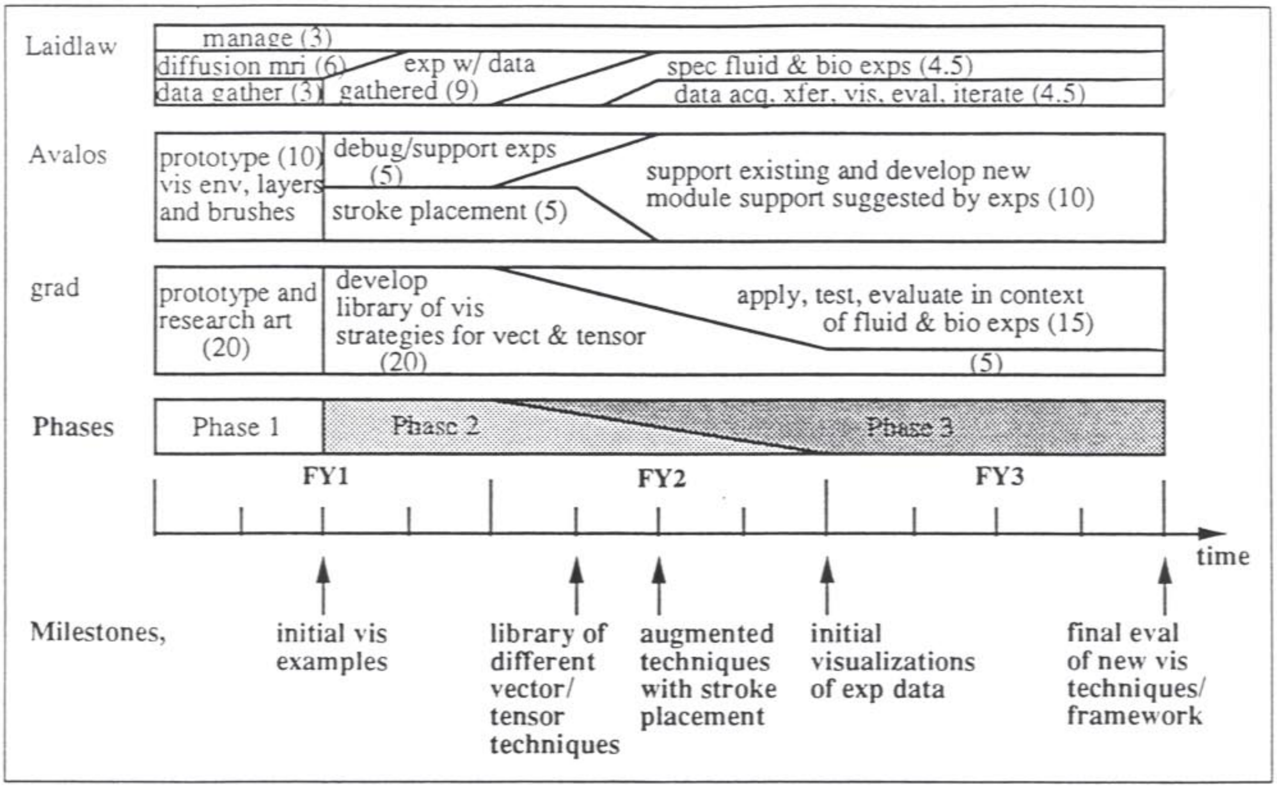

Figure 5: Timeline for this project. (N) indicates number of hours per week for each portion of project. Significant experimentation is expected both in the initial development of a library of visualization strategies and in the application of the strategies to measurements of fluid and biological systems.

4.1.3 Gather Fluid Data

A third phase-1 effort will involve gathering data of turbulent fluid flow for experimentation with visualization algorithms in the second phase.

4.2 Phase 2: Visualization Strategy Specification and Experimentation

During the second phase the initial computational framework will be used to explore the space of visualizations using the data gathered during the first phase and to develop a library of visualization techniques. This work will uncover bugs and limitations in the framework, which will be repaired and extended as necessary.

Likely second-phase extensions will allow curved brush strokes, allow color and texture to be modified across a single stroke, and allow more sophisticated placement of brush strokes. Stochastic stroke locations are likely to be effective for planar data, but more sophisticated techniques [Turk and Banks, 1996] [Fleischer et al., 1995] [Meier, 1996] will be more effective for data defined over a surface or volume.

4.3 Phase 3: Application and Evaluation

During the third phase of the project we will choose from the library of visualization tools and apply selected ones to the problems described in Section 3. This phase will be iterative, as Figure 1 shows; as in phase 2, we expect to continue to extend the framework to accommodate limitations. Ultimately, the success of the strategies will be determined as a measure of the insight generated through the iterative experimental process of hypothesis, measurement, visualization, and modeling.

5 Summary

Our three-phase project proposes to produce novel and effective visualization techniques for understanding vector-field and tensor-field measurements and the physical systems and phenomena they measure. The facilities at Caltech and the multi-disciplinary collaborations already in place will help to ensure success through providing scientific direction, volume measurements, and evaluation criteria in the search for techniques. The resulting techniques, which will build upon many existing techniques, will provide a more holistic view of the measurements and provide more sample points in the currently sparsely-sampled space of vector- and tensor-field visualizations.

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BIOGRAPHICAL SKETCH

Provide the following information for the senior personnel on the project. Begin with the Principal Investigator/Project Director.
DO NOT EXCEED 2 PAGES PER PERSON

A. Vitae, listing professional and academic essentials and mailing address.
B. List up to 5 publications most closely related to the proposed project and up to 5 other significant publications, including those being printed. Patents, copyrights, or software systems developed may be substituted for publications. Do not include additional lists of publications, invited lectures, etc. Only the list of up to 10 will be used in merit review.
C List of persons, other than those cited in the publication list, who have collaborated on a project or a book, article, report or paper within the last 48 months, including collaborators on this proposal. If there are no other collaborators, please indicate that fact.
D. Names of graduate and post-graduate advisors and advisees.
The information in C. and D. is used to help identify potential conflicts or bias in the selection of reviewers.

A. PERSONAL

Name:	David H. Laidlaw
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EDUCATION

1983 Sc.B. in Computer Science, Brown University, Providence, RI
1985 Sc.M. in Computer Science, Brown University, Providence, RI
1992 M.S. in Computer Science, California Institute of Technology, Pasadena, CA
1995 Ph.D. in Computer Science, California Institute of Technology, Pasadena, CA

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Earl C. Anthony Graduate Fellowship
Sigma Xi
Who's Who in the West
ACM Siggraph paper reviewer

EMPLOYMENT

1980-82	Programmer, Johns Hopkins University
1983	Teaching Assistant, Brown University
1984	Consultant, Basel Institute for Immunology, Switzerland
1983-1985	Research Assistant, Brown University
1986-1989	Software Engineer, Stellar Computer
1989-1993	Consultant Stardent/Advanced Visual Systems
1989-1996	Postdoctoral Research Fellow/Research Assistant, California Institute of Technology
1996-present	Senior Research Fellow, Division of Biology, California Institute of Technology

B. PUBLICATIONS

Five Most Closely Related to Project

Laidlaw, D. H., Barr, A. H, and Jacobs, R. E. Goal-directed brain micro-imaging. In *Neuroinformatics: An Overview of the Human Brain Project*, vol 1 of *Progress in Neuroinformatics*, in press.

Laidlaw, D. H. (1995). Geometric Model Extraction from Magnetic Resonance Volume Data. Ph.D. Thesis, Technical Report CS-TR-95-05, California Institute of Technology.

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<u>Five Other Significant Publications</u>

Laidlaw, D. H., Fleischer, K. W., and Barr, A. H. (1995). Bayesian Mixture Classification of MRI Data for Geometric Modeling and Visualization. Abstract and poster for International Workshop on Mixtures, Aussois, France, September 17-21.

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Laidlaw, D. H., Banchoff, T. F, Kocak, H, Bisshopp, F., and Margolis, D. M. (1985). Film "*The Hypersphere: Foliations and Projections*," Siggraph Animation Screening; Siggraph Video Review, 1986; Siggraph Art Show, 1986.

C. Collaborators: Eric Ahrens, Jim Narasimhan, Ronen Barzel, John Allman, Scott Fraser

D. Graduate students: none

E. Graduate Advisor: Alan Barr
Post-Graduate Advisor: Alan Barr

SUMMARY PROPOSAL BUDGET

Year 1 of 3 — 4/1/97 to 3/31/98

ORGANIZATION California Institute of Technology	FOR NSF USE ONLY				
	PROPOSAL NO.:			DURATION (MONTHS)	
				Proposed	Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR David Laidlaw	AWARD NO.				
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and other Senior Associates (List each separately with title, A.7 show number in brackets)	NSF Funded Person-months			Funds Requested By Proposer	Funds Granted By NSF (If Different)
	CAL	ACAD	SUMR		
1. David Laidlaw	3.6			[redacted]	
2.					
3.					
4.					
5.					
6.( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. ( ) TOTAL SENIOR PERSONNEL (1-6)	3.6			[redacted]	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1.( ) POST DOCTORAL ASSOCIATES					
2.(1) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	3.6			[redacted]	
3.(1) GRADUATE STUDENTS				[redacted]	
4.( ) UNDERGRADUATE STUDENTS					
5.( ) SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)					
6.(1) OTHER				[redacted]	
TOTAL SALARIES AND WAGES (A+B)				[redacted]	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				[redacted]	
TOTAL SALARIES, WAGES, AND FRINGE BENEFITS (A+B+C)				[redacted]	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) 9 gigabyte SCSI drives (3) 6000 Personal computer 4000 SGI workstation 25000					
TOTAL EQUIPMENT				[redacted]	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				[redacted]	
2. FOREIGN					
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 2. TRAVEL 3. SUBSISTENCE 4. OTHER					
( ) TOTAL PARTICIPANT COSTS					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				[redacted]	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				[redacted]	
3. CONSULTANT SERVICES					
4. COMPUTER SERVICES				[redacted]	
5. SUBAWARDS					
6. OTHER tuition remission				[redacted]	
TOTAL OTHER DIRECT COSTS				[redacted]	
H. TOTAL DIRECT COSTS (A THROUGH G)				[redacted]	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) 56% excluding equipment tuition and remission					
TOTAL INDIRECT COSTS				[redacted]	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				[redacted]	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECT SEE GPG II.D.7.j.)					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				[redacted]	
M. COST SHARING: PROPOSED LEVEL $	AGREED LEVEL IF DIFFERENT $				

PI/PD TYPED NAME & SIGNATURE *	DATE	FOR NSF USE ONLY — INDIRECT COST RATE VERIFICATION		
		Date Checked	Date of Rate Sheet	Initials-DGC
INST. REP. TYPED NAME & SIGNATURE	DATE			

* SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPG III.B)

SUMMARY PROPOSAL BUDGET	Year 2 of 3	4/1/98 to 3/31/99			
	FOR NSF USE ONLY				
ORGANIZATION California Institute of Technology	PROPOSAL NO.:			DURATION (MONTHS) Proposed	Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR David Laidlaw	AWARD NO.				
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and other Senior Associates (List each separately with title, A.7 show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted By NSF (If Different)
1. David Laidlaw	3.6			[redacted]	
2.					
3.					
4.					
5.					
6.( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. ( ) TOTAL SENIOR PERSONNEL (1-6)	3.6			[redacted]	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1.( ) POST DOCTORAL ASSOCIATE					
2.(1) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	3.6			[redacted]	
3.(1) GRADUATE STUDENTS				[redacted]	
4.( ) UNDERGRADUATE STUDENTS					
5.( ) SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)					
6.(1) OTHER				[redacted]	
TOTAL SALARIES AND WAGES (A+B)				[redacted]	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				[redacted]	
TOTAL SALARIES, WAGES, AND FRINGE BENEFITS (A+B+C)				[redacted]	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				[redacted]	
2. FOREIGN					
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ ____ 2. TRAVEL ____ 3. SUBSISTENCE ____ 4. OTHER ____					
( ) TOTAL PARTICIPANT COSTS					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				[redacted]	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				[redacted]	
3. CONSULTANT SERVICES					
4. COMPUTER SERVICES				[redacted]	
5. SUBAWARDS					
6. OTHER tuition remission				[redacted]	
TOTAL OTHER DIRECT COSTS				[redacted]	
H. TOTAL DIRECT COSTS (A THROUGH G)				[redacted]	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) 56% excluding tuition remission					
TOTAL INDIRECT COSTS				[redacted]	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				[redacted]	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECT SEE GPG II.D.7.j.)					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				[redacted]	
M. COST SHARING: PROPOSED LEVEL $	AGREED LEVEL IF DIFFERENT $				

PI/PD TYPED NAME & SIGNATURE *	DATE	FOR NSF USE ONLY		
		INDIRECT COST RATE VERIFICATION		
INST. REP. TYPED NAME & SIGNATURE	DATE	Date Checked	Date of Rate Sheet	Initials-DGC

* SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPG III.B)

SUMMARY PROPOSAL BUDGET

Year 3 of 3 — 4/1/99 to 3/31/00

	FOR NSF USE ONLY	
ORGANIZATION California Institute of Technology	PROPOSAL NO.:	DURATION (MONTHS): Proposed / Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR David Laidlaw	AWARD NO.	

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and other Senior Associates (List each separately with title, A.7 show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted By NSF (If Different)
1. David Laidlaw	3.6			[redacted]	
2.					
3.					
4.					
5.					
6.( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. ( ) TOTAL SENIOR PERSONNEL (1-6)	3.6			[redacted]	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1.( ) POST DOCTORAL ASSOCIATES					
2.(1) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	3.6			[redacted]	
3.(1) GRADUATE STUDENTS				[redacted]	
4.( ) UNDERGRADUATE STUDENTS					
5.( ) SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)					
6.(1) OTHER				[redacted]	
TOTAL SALARIES AND WAGES (A+B)				[redacted]	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				[redacted]	
TOTAL SALARIES, WAGES, AND FRINGE BENEFITS (A+B+C)				[redacted]	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TC TOTAL EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				[redacted]	
2. FOREIGN					
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 2. TRAVEL 3. SUBSISTENCE 4. OTHER					
( ) TOTAL PARTICIPANT COSTS					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				[redacted]	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				[redacted]	
3. CONSULTANT SERVICES					
4. COMPUTER SERVICES				[redacted]	
5. SUBAWARDS					
6. OTHER tuition remission				[redacted]	
TOTAL OTHER DIRECT COSTS				[redacted]	
H. TOTAL DIRECT COSTS (A THROUGH G)				[redacted]	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) 56% excluding tuition remission					
TOTAL INDIRECT COSTS				[redacted]	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				[redacted]	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECT SEE GPG II.D.7.j.)					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				[redacted]	
M. COST SHARING: PROPOSED LEVEL $		AGREED LEVEL IF DIFFERENT $			

		FOR NSF USE ONLY		
PI/PD TYPED NAME & SIGNATURE *	DATE	INDIRECT COST RATE VERIFICATION		
INST. REP. TYPED NAME & SIGNATURE	DATE	Date Checked	Date of Rate Sheet	Initials-DGC

* SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPG III.B)

SUMMARY PROPOSAL BUDGET

Cumulative 4/1/97 to 3/31/00

ORGANIZATION California Institute of Technology	PROPOSAL NO.:	DURATION (MONTHS): Proposed / Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR David Laidlaw	AWARD NO.	

FOR NSF USE ONLY

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and other Senior Associates (List each separately with title, A.7 show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted By NSF (If Different)
1. David Laidlaw	10.8			[redacted]	
2.					
3.					
4.					
5.					
6.( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. ( ) TOTAL SENIOR PERSONNEL (1-6)	10.8			[redacted]	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1.( ) POST DOCTORAL ASSOCIATES					
2.(1) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	10.8			[redacted]	
3.(1) GRADUATE STUDENTS				[redacted]	
4.( ) UNDERGRADUATE STUDENTS					
5.( ) SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)					
6.(1) OTHER				[redacted]	
TOTAL SALARIES AND WAGES (A+B)				[redacted]	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				[redacted]	
TOTAL SALARIES, WAGES, AND FRINGE BENEFITS (A+B+C)				[redacted]	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TC TOTAL EQUIPMENT				[redacted]	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				[redacted]	
2. FOREIGN					
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 2. TRAVEL 3. SUBSISTENCE 4. OTHER					
( ) TOTAL PARTICIPANT COSTS					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				[redacted]	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				[redacted]	
3. CONSULTANT SERVICES					
4. COMPUTER SERVICES				[redacted]	
5. SUBAWARDS					
6. OTHER				[redacted]	
TOTAL OTHER DIRECT COSTS				[redacted]	
H. TOTAL DIRECT COSTS (A THROUGH G)				[redacted]	
I. INDIRECT COSTS (SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS				[redacted]	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				[redacted]	
K. RE RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECT SEE GPG II.D.7.j.)					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				[redacted]	

M. COST SHARING: PROPOSED LEVEL $ AGREED LEVEL IF DIFFERENT $

PI/PD TYPED NAME & SIGNATURE *	DATE	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION
INST. REP. TYPED NAME & SIGNATURE	DATE	Date Checked / Date of Rate Sheet / Initials-DGC

* SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPG III.B)

NSF Budget Justification

Personnel The principal investigator, Dr. David Laidlaw, plans to spend about 30% of his time on this project. This project is an important part of his long-term research efforts in creating computational and visualization tools for science. Dr. Laidlaw is a new investigator in a soft-money position, and this project will help him to develop a sustainable independent research program.

Part of his effort will be spent in managing the other participants in the project and the remainder in participating closely in the specification and development of the computational framework and specific visualization strategies. Interdisciplinary projects require relationships that take a significant time to maintain, and yet are essential. Dr. Laidlaw will be maintaining relationships with the Biological Imaging Center and with the Department of Aeronautics.

Mr. Avalos has worked with Dr. Laidlaw for four years, and is familiar with image processing, with AVS, and with the volume data manipulation software in the Caltech graphics lab. As such, he is the ideal person to provide programming support for the computational environment. Without his support at a level of 10 hours per week, the work will be proportionately delayed.

Portions of this work are ideal for a grad student to work on in conjunction with Mr. Avalos and Dr. Laidlaw. The grad student will be responsible for experimentation with visualization techniques, for evaluating their efficacy in conjunction with Dr. Laidlaw and with the scientists in biology and fluid mechanics.

Dr. David Breen is the assistant director of the graphics lab at Caltech, and is responsible for keeping the significant graphics facilities available and in working order, and for providing support in grant preparation and reporting. Without his assistance, which is expected to take about 5% of his time, the PI will have to spend more than 5% of his time performing those tasks to which Dr. Breen is particularly well suited.

Equipment The multi-valued volume datasets acquired require prodigious amounts of disk space, and while some hardware is available for the computation, sufficient disk space is not. $6000 will purchase three 9-gigabyte SCSI drives that will serve this need over the 3 year period.

Dr. Laidlaw will be able to work much more effectively on writing, programming, and monitoring of some computations with a home computer that can access the Caltech machines. The computer, software, and connection setup are estimated to cost $4000.

A dedicated SGI for Matthew Avalos to work on will make him far more productive and enhance our collaboration with the Biological Imaging Center. Mr. Avalos currently has access to several non-SGI Unix workstations, but no access to SGI's, which are the machines that the biological imaging center uses for MRI acquisitions. Such a machine will allow more effective interoperation with the imaging center, easing the process of exchanging files, datasets, and software. Currently, any software produced must be ported to an SGI before it can be used in the imaging center.

Materials and Supplies In establishing an independent research program, Dr. Laidlaw will need to buy books that are routinely needed for reference, or that are not accessible via the library. He anticipates that $500 will supply those needs for this project each year. Similarly, copying, reprint charges, and library searches will be essential for this work, and are expected to be about $200 per year.

Publication Costs/Documentation/Dissemination $2260/yr are requested to cover typical publication costs for one or two journal papers with color plates per year.

Computer Services Support for single Unix workstations is essential. Experience shows that it is more expensive to pay-as-you-go, and also much less predictable. Without support, the machine will likely be usable for only 18 months.

Travel Siggraph is the premier computer graphics conference, and my attendance is essential in order to keep up with developments and contacts in graphics and visualization that will impact this work. Siggraph costs approximately $1500. The IEEE sponsored Visualization conference is of similar import for the visualization aspects of this work, and costs approximately $900.

Fringe Benefits And Tuition Remission The fringe benefit rate through 9/30/97 of year 1 is 33.34% of all salaries excluding undergraduate students. Effective 10/1/97, fringe benefits are calculated at 25% for faculty and staff and exclude graduate and undergraduate students. Institute policy is to provide each graduate student employee, who meets a required average work week, with full tuition and fees. The tuition remission rate of 80% of the graduate student stipend is effective 10/1/97 and is listed in the Other Expenses category.

Current and Pending Support

(See GPG Section II.D.8 for guidance on Information to Include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: David Laidlaw

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ * Transfer of Support

Project/Proposal Title: Goal-Directed Model Acquisition and Rendering

Source of Support: NIH (Alan Barr)

Total Award Amount: [redacted]

Total Award Period Covered: 9/30/93-8/31/98

Location of Project: California Institute of Technology

Person-Months Per Year Committed to the Project. Cal: 2.4 Acad: Sumr:

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ * Transfer of Support

Project/Proposal Title: Goal-Directed Magnetic Resonance Brain Micro-Imaging

Source of Support: NSF (Russell Jacobs)

Total Award Amount: [redacted]

Total Award Period Covered: 9/15/94-8/31/98

Location of Project: California Institute of Technology

Person-Months Per Year Committed to the Project. Cal: 3.6 Acad: Sumr:

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ * Transfer of Support

Project/Proposal Title: Science and Technology Center for Computer Graphics and Scientific Visualization (for geometric model extraction work)

Source of Support: NSF (Alan Barr)

Total Award Amount: [redacted]

Total Award Period Covered: 2/1/91-1/31/97

Location of Project: California Institute of Technology

Person-Months Per Year Committed to the Project. Cal: 2.4 Acad: Sumr:

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ * Transfer of Support

Project/Proposal Title: Acquisition and Visualization of Tensor-valued Volume Data: A Painting Metaphor

Source of Support: NSF

Total Award Amount: [redacted]

Total Award Period Covered: 4/1/97-3/31/00

Location of Project:

Person-Months Per Year Committed to the Project. Cal: 3.6 Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ * Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount:

Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

---

* If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

FACILITIES, EQUIPMENT & OTHER RESOURCES

FACILITIES: Identify the facilities to be used at each performance site listed and, as appropriate, indicate their capacities, pertinent capabilities, relative proximity, and extent of availability to the project. Use "Other" to describe the facilities at any other performance sites listed and at sites for field studies. Use additional pages if necessary.

Laboratory:

Clinical:

Animal:

Computer:

Part-time use of 7 HP Unix workstations, 4 DEC Alpha Unix workstations, 4 IBM RS/6000 workstations, all equipped to run AVS.

Office:

344 Beckman Institute for Dr. Laidlaw and computer lab space in 325 Beckman Institute for Mr. Avalos.

Other: ____________________

MAJOR EQUIPMENT: List the most important items available for this project and, as appropriate, identify the location and pertinent capabilities of each.

AMX-500 11.7 T Magnetic Resonance Micro-Imaging system
Turbulent Flow Laser-Imaging system

OTHER RESOURCES: Provide any information describing the other resources available for the project. Identify support services such as consultant, secretarial, machine shop, and electronics shop, and the extent to which they will be available for the project. Include an explanation of any consortium/contractual/subaward arrangements with other organizations.

CALIFORNIA INSTITUTE OF TECHNOLOGY

DIVISION OF BIOLOGY
PASADENA, CALIFORNIA
91125

BECKMAN INSTITUTE
BIOLOGICAL IMAGING CENTER
MAIL CODE 139-74
FACSIMILE (818) 449-5163
TELEPHONE (818) 395-2790

Scott E. Fraser, Ph.D.
Anna L Rosen Professor of Biology

September 9, 1996

Dr. David Laidlaw
Beckman Institute
California Institute of Technology
Pasadena, CA 91125

Dear David,

I am happy to agree to collaborate with you in your new research program. I see it as a program that can have very important impacts on our ability to do biological imaging.

As you know, one of our major problems in the Biological Imaging Center has been to comprehend the complex data sets that we are capable of collecting. In light microscopy, we can collect intensity, wavelength, fluorescence lifetime, and several other key aspects of the signal. In MRI, there are even more variables, ranging from the relaxation times to diffusion. Your efforts appear to have an excellent chance of filling the important gap between the data we can collect and the data we can visualize.

The Biological Imaging Center should prove to be fertile ground for your work. The nearly three dozen members of the Center collect a wide variety of data sets, and, because they come from several different backgrounds, should be able to give you feedback on the work from several different perspectives. We welcome your active participation in this interdisciplinary mix.

Sincerely yours,

Scott E. Fraser

GRADUATE AERONAUTICAL LABORATORIES
CALIFORNIA INSTITUTE of TECHNOLOGY
Pasadena, California 91125

Mail Code 301–46 *Tel: (818) 395–4456*
E-mail: dimotakis@caltech.edu *Fax: (818) 395–4447*

12 September 1996

Dr. David H. Laidlaw
Caltech 139–74
Pasadena, CA 91125

Dear David,

This letter is in support of your proposal, "Computer graphics tools for understanding tensor-valued volume data: a painting metaphor," to the National Science Foundation. In my opinion, the proposed effort promises to develop visualization tools that would be invaluable in the field of fluid mechanics, in general, and turbulence, in particular.

Specifically, fluid mechanics in its many realizations is forced to deal with vector and tensor fields. Progress in this technologically- and theoretically-important area has been hampered by a paucity of both data of this kind as well as visualization and quantitative analysis tools for such data. The advent of digital imaging and multi-dimensional-data acquisition technology, however, is providing us with exactly the kind of data you are proposing to analyze with the new tools. Such a contribution would be a significant addition to the means available for us to understand the complex geometry and dynamics of turbulence, for example.

We are looking forward to a strong collaboration with you and your expert assistance in the analysis of the various forms of multi-dimensional data we expect to be acquiring in the laboratory in the near future.

Sincerely,

Paul E. Dimotakis
John K. Northrop Professor of
Aeronautics and Professor of
Applied Physics

pxd471.ltr

CALIFORNIA INSTITUTE OF TECHNOLOGY

James Arvo
COMPUTER SCIENCE 256-80
PASADENA, CALIFORNIA 91125

+1(818)395-6780
FAX: +1(818)792-4257
arvo@cs.caltech.edu

12 September 1996

Dr. David Laidlaw
Beckman Institute
California Institute of Technology
Pasadena, CA 91125

Dear David:

I believe that the approach that you describe in your research proposal is sound and represents a promising research direction for a wide range of visualization tasks. I am entheusiastic about the use of painting techniques to create rich visual representations. I have enjoyed participating in some of the early discussions regarding this work, and look forward to collaborating on the project in any that way is appropriate.

Sincerely,

James Arvo

James Arvo
Professor of Computer Science

ADVANCED
VISUAL
SYSTEMS
INC.

September 11, 1996

Dr. David Laidlaw
Senior Research Fellow
Caltech M/S 350-74
1200 E. California Blvd
Pasadena, CA 91125

Dear David:

Your research project to develop new strategies for visualizing multi-valued multi-variate data sounds very promising, and we at Advanced Visual Systems are excited about being involved. Visualization of such data is one of the more difficult problems for many visualization products, and your results have the potential to be very interesting to some of our medical imaging and computational fluid dynamics customers. We are always searching for ways to provide our customers access to techniques that are more effective, easier to use, and more widely applicable, and we have high hopes for this work.

In support of the project we will donate a floating license to run AVS on your machines. We will also be available to answer any questions about AVS that arise during the development. Your feedback on AVS and ideas for enhancements are welcome. We look forward to working with you to help your project be a success.

Sincerely,

Ham

Hambleton Lord
Vice President, Industry Marketing

300 Fifth Avenue
Waltham, MA 02154
617-890-4300 TEL
617-890-8287 FAX

CALIFORNIA INSTITUTE OF TECHNOLOGY

DIVISION OF BIOLOGY
PASADENA, CALIFORNIA
91125

BECKMAN INSTITUTE
BIOLOGICAL IMAGING CENTER
MAIL CODE 139-74
FACSIMILE (818) 449-5163
TELEPHONE (818) 395-2863
EMAIL: ETA@DRUGGIST.GG.CALTECH.EDU

Eric T. Ahrens, Ph.D.
Research Fellow

11 September 1996

Dear David:

This letter is to express my willingness to continue our collaboration on your studies of visualization of diffusion tensor fields. I agree to provide for you high resolution three-dimensional magnetic resonance image data in order to boot-strap your visualization algorithms. I believe that our joint work will make a major impact in advancing the state-of-the-art of neuro-imaging. This work will be particularly important in the field of axonal visualization of the central nervous system, which is a classic problem in neuroscience. In addition, because MRI acquisitions are compatible with *in vivo* investigations, these new visualization capabilities will provide new insights into the basic understanding of neurological diseases, such as multiple sclerosis.

I look forward to our continued collaboration.

Sincerely yours,

Eric T. Ahrens

CALIFORNIA INSTITUTE OF TECHNOLOGY

Pasadena, California 91125

Office of Sponsored Research
(818) 395-6357

Mail Stop 213-6
Fax: (818) 795-4571

January 7, 1997

Dr. Kamal Abdali
Division of CCR
Numeric, Symbolic and Geometric
Computation Program
NATIONAL SCIENCE FOUNDATION
4201 Wilson Blvd.
Arlington, VA 22230

Subject: Revised Budget entitled:
"Computer Graphics Tools for Understanding Tensor-Valued Volume Data: A Painting Metaphor "
Proposal I.D. No. CCR-9619649
1 February 1997 - 30 June 1998
[redacted]
1 February 1997 - 31 January 1998
[redacted]

Dear Dr. Abdali:

Enclosed for your consideration is a revised budget (original and 2 copies), prepared by Dr. David Laidlaw on the above referenced proposal I. D. No.

Thank you for your time and effort on behalf of the Institute.

Sincerely yours,

Richard P. Seligman
Director, Sponsored Research

RPS:gu

cc: Dr. D. Laidlaw - CIT
Dr. M. Simon - CIT (156-29)

SUMMARY PROPOSAL BUDGET

Year 2 of 2 — 2/1/98 to 6/30/98

ORGANIZATION	FOR NSF USE ONLY		
California Institute of Technology	PROPOSAL NO.:	DURATION (MONTHS) Proposed	Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR David Laidlaw	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and other Senior Associates (List each separately with title, A.7 show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted By NSF (If Different)
1. David Laidlaw	0.8			[redacted]	
2.					
3.					
4. 40% support for second year					
5.					
6.( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. ( ) TOTAL SENIOR PERSONNEL (1-6)	1.0			[redacted]	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1.( ) POST DOCTORAL ASSOCIATES					
2.(1) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	1.44			[redacted]	
3.(1) GRADUATE STUDENTS				[redacted]	
4.( ) UNDERGRADUATE STUDENTS					
5.( ) SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)					
6.( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				[redacted]	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				[redacted]	
TOTAL SALARIES, WAGES, AND FRINGE BENEFITS (A+B+C)				[redacted]	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				[redacted]	
2. FOREIGN					
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 2. TRAVEL 3. SUBSISTENCE 4. OTHER					
( ) TOTAL PARTICIPANT COSTS					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				[redacted]	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				[redacted]	
3. CONSULTANT SERVICES					
4. COMPUTER SERVICES				[redacted]	
5. SUBAWARDS					
6. OTHER tuition remission				[redacted]	
TOTAL OTHER DIRECT COSTS				[redacted]	
H. TOTAL DIRECT COSTS (A THROUGH G)				[redacted]	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) 57.45% excluding tuition remission					
TOTAL INDIRECT COSTS				[redacted]	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				[redacted]	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECT SEE GPG II.D.7.j.)					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				[redacted]	

M. COST SHARING: PROPOSED LEVEL $		AGREED LEVEL IF DIFFERENT $		
PI/PD TYPED NAME & SIGNATURE *	DATE 1/2/97	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
INST. REP. TYPED NAME & SIGNATURE	DATE 1-2-97	Date Checked	Date of Rate Sheet	Initials-DGC

* SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPG III.B)

SUMMARY
PROPOSAL BUDGET

Year 1 of 2 — 2/1/97 to 1/31/98

FOR NSF USE ONLY

ORGANIZATION California Institute of Technology	PROPOSAL NO.:			DURATION (MONTHS) Proposed	Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR David Laidlaw	AWARD NO.				

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and other Senior Associates (List each separately with title, A.7 show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted By NSF (If Different)
1. David Laidlaw	2.0			[redacted]	
2.					
3.					
4.					
5.					
6.( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. ( ) TOTAL SENIOR PERSONNEL (1-6)	2.0			[redacted]	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1.( ) POST DOCTORAL ASSOCIATES					
2.(1) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	3.6			[redacted]	
3.(1) GRADUATE STUDENTS				[redacted]	
4.( ) UNDERGRADUATE STUDENTS					
5.( ) SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)					
6.( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				[redacted]	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				[redacted]	
TOTAL SALARIES, WAGES, AND FRINGE BENEFITS (A+B+C)				[redacted]	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) 9 gigabyte SCSI drives (3) 2000 SGI workstation (50%) 18000					
TOTAL EQUIPMENT				[redacted]	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				[redacted]	
2. FOREIGN					
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ ____ 2. TRAVEL ____ 3. SUBSISTENCE ____ 4. OTHER ____					
( ) TOTAL PARTICIPANT COSTS					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				[redacted]	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				[redacted]	
3. CONSULTANT SERVICES					
4. COMPUTER SERVICES				[redacted]	
5. SUBAWARDS					
6. OTHER tuition remission				[redacted]	
TOTAL OTHER DIRECT COSTS				[redacted]	
H. TOTAL DIRECT COSTS (A THROUGH G)				[redacted]	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) 57.45% excluding equipment tuition and remission					
TOTAL INDIRECT COSTS				[redacted]	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				[redacted]	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECT SEE GPG II.D.7.j.)					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				[redacted]	

M. COST SHARING: PROPOSED LEVEL $ — AGREED LEVEL IF DIFFERENT $

PI/PD TYPED NAME & SIGNATURE *	DATE	FOR NSF USE ONLY — INDIRECT COST RATE VERIFICATION		
[signature]	1/2/97	Date Checked	Date of Rate Sheet	Initials-DGC
INST. REP. TYPED NAME & SIGNATURE [signature]	DATE 1-2-97			

NSF Form 1030 (7/95) *Supersedes All Previous Editions* — * SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPG III.B)

CALIFORNIA INSTITUTE OF TECHNOLOGY
DIVISIONAL APPROVAL FORM FOR SPONSORED RESEARCH PROPOSALS

Principal Investigator(s): David Laidlaw

Agency/Company: NSF
If JPL give contact name:
Agency due date:

PROJECT TITLE: Computer Graphics Tools for Understanding Tensor-valued Volume Data: A Painting Metaphor

Amount Requested for 1st budget period: $ [redacted]
Amount Requested for entire project period: [redacted]
Requested performance period: 2 year(s)/month(s):
from: 2/1/97 ~~4/1/97~~ to 6/30/98
Please allow 3 working days for processing.
Note: This COMPLETED form must accompany each proposal submitted to the Office of Sponsored Research for review and Institute signature. Use additional pages as required.

TYPE OF PROPOSAL:
☐ Renewal ☐ New
☐ Continuation ☒ Revision (Budget)
☐ Supplement ☐ Response to RFP or BAA
For any of the above provide the following: ☐ (Provide copy)
CIT Account #:
Agency #:

1. OVERALL GRANT & CONTRACT SUPPORT OF FACULTY SALARIES
(Include all PI's and Professorial faculty involved in this research.)

Name	>30%	21-30%	15-20%	<15%
David Laidlaw	☐	☐	☐	☒
	☐	☐	☐	☐
	☐	☐	☐	☐

2. INDIRECT COST COMPUTATION
a. ☒ Standard ☐ Non-Standard
If using non-standard rates, are rates a written Sponsor policy?
b. ☐ No ☐ Yes (Attach copy of policy)
For non-standard amounts, list amount of general budget salaries and other costs that have been included to offset unrecovered indirect costs.
$ of Salary.
$ of other General Budget Costs.

3. SPACE OR INSTITUTE COMMITMENTS
a. Will additional space be required? ☒ No ☐ Yes
b. Is rehabilitation of existing space required? ☒ No ☐ Yes
c. Are Institute funds required for cost sharing? ☒ No ☐ Yes
d. Is the proposed Sponsor likely to request deviations from the Institute's normal policies on ownership of patens or data or its unrestricted right to publish research results? ☒ No ☐ Yes
If answer to any of the above is yes, attach a separate sheet explaining how the financial commitment is to be met or the nature of the deviation from Institute policy.

4. GRA SUPPORT
Amount requested: $ [redacted] # of students: 1
a. If no GRA support, what is the reason?

b. Give number of graduate students on project supported by other funding.

Support Source	# of Students	GTA or GRA
-	0	-

PRINCIPAL INVESTIGATORS
By signing this form I acknowledge that I will comply with Institute policies and sponsoring agency terms and conditions, if an award is made. Further, for Federal sponsors, I acknowledge that I have read the relevant certifications and regulations governing Federal awards reproduced on the back of this form, I will report any exceptions or violations to the Vice Provost or his designee, I have made all participants aware of regulations regarding financial conflict of interest and where necessary, all financial disclosures have been made.

Signature: [signature]

Signature:
PROVOST (signature approves P.I. or Co-P.I. who does not hold Professorial rank.)

Signature:

5. Does the proposed research involve the use of human subjects
☒ No ☐ Yes
If yes, give date of IRB review & approval:
If not yet reviewed, give status of review
☐ Requested expedited review
☐ Exempt under section of HHS regulations
☐ Submitted for IRB review on

6. Does the proposed research involve the use of animals?
☒ No ☐ Yes Date of IACUC approval:

7. Does the proposed research involve the use of recombinant DNA molecules, viral vectors, or transgenics?
☒ No ☐ Yes
If yes, please answer the following:
☐ Project reported to Biosafety Committee.
☐ Project registered and approved by Biosafety Committee on (Date)
☐ Project exempt (cite reason per NIH Regulation.) Reason:

8. Does the proposed research involve the use of reactive chemicals, toxic gases, radioactive material, or other extreme radiation-producing devices?
☒ No ☐ Yes
(If "yes", supply an extra copy of the proposal for the Safety Office.)

9a. Could any Institute participants (including their spouses and/or dependent children, if any) financially benefit directly or do they have a significant financial interest in an entity that would financially benefit from the results of the research or instructional activities contained in this proposal?
☒ No ☐ Yes (See 9b.)

9b. If the answer to 9a. is yes for any participants in the project, have they made the required financial disclosure?
☐ No **Proposal cannot be mailed until disclosure is made.**
☐ Yes Date of disclosure:

DIVISION CHAIR'S APPROVAL
I have reviewed the proposed project and the responses on this Division Approval Form and concur that this project is acceptable to the Division and recommend approval by the Institute.

Signature: Mel Simon (acting)
DEAN OF GRADUATE STUDENTS (Training Grant Applications)

Signature:
BUSINESS & FINANCE OFFICE

Signature:

Rev 9.95

SUMMARY PROPOSAL BUDGET	Cumulative	2/1/97 to 6/30/98

FOR NSF USE ONLY

ORGANIZATION California Institute of Technology	PROPOSAL NO.:	DURATION (MONTHS) Proposed	Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR David Laidlaw	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and other Senior Associates (List each separately with title, A.7 show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted By NSF (If Different)
1. David Laidlaw	2.8			[redacted]	
2.					
3.					
4.					
5.					
6.( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. ( ) TOTAL SENIOR PERSONNEL (1-6)	2.8			[redacted]	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1.( ) POST DOCTORAL ASSOCIATES					
2.(1) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	5.04			[redacted]	
3.(1) GRADUATE STUDENTS				[redacted]	
4.( ) UNDERGRADUATE STUDENTS					
5.( ) SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)					
6.(1) OTHER					
TOTAL SALARIES AND WAGES (A+B)				[redacted]	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				[redacted]	
TOTAL SALARIES, WAGES, AND FRINGE BENEFITS (A+B+C)				[redacted]	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TC TOTAL EQUIPMENT				[redacted]	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				[redacted]	
2. FOREIGN					
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ ____ 2. TRAVEL ____ 3. SUBSISTENCE ____ 4. OTHER ____					
( ) TOTAL PARTICIPANT COSTS					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				[redacted]	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				[redacted]	
3. CONSULTANT SERVICES					
4. COMPUTER SERVICES				[redacted]	
5. SUBAWARDS					
6. OTHER				[redacted]	
TOTAL OTHER DIRECT COSTS				[redacted]	
H. TOTAL DIRECT COSTS (A THROUGH G)				[redacted]	
I. INDIRECT COSTS (SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS				[redacted]	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				[redacted]	
K. RE RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECT SEE GPG II.D.7.j.)					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				[redacted]	

M. COST SHARING: PROPOSED LEVEL $		AGREED LEVEL IF DIFFERENT $
PI/PD TYPED NAME & SIGNATURE *	DATE 1/2/97	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION
INST. REP. TYPED NAME & SIGNATURE	DATE 1-2-97	Date Checked | Date of Rate Sheet | Initials-DGC

NSF Form 1030 (7/95) *Supersedes All Previous Editions* * SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPG III.B)

Because of the reduced budget and period of effort, the scope of the project will be modified as follows:

1. The research proposed in Section 4.1 be carried out as described.

2. The research proposed in Sections 4.2 will be done if time and funds permit.

3. The research proposed in Sections 4.3 will not be attempted.