The core focus of my research is on developing software tools and technologies to support the creation of augmented and mixed reality experiences (AR for short), especially the fundamental (and often subtle) problems that have made augmented reality systems difficult to design and deploy. In my research, I prefer not to focus on a specific aspect of AR software and technology (such as tracking technology or interaction techniques) but to rather consider all aspects of AR as a new medium for use in authentic situations. I believe the best way to accomplish this is to form deep collaborations with people who are attempting to solve real problems using AR. Therefore, I have developed long-term collaborations with researchers, theoreticians and practitioners in the military, industrial, design and artistic communities, and have leveraged these collaborative experiences to inform my own research.

The main reason I am committed to working on real problems (from art and entertainment, to military and industrial applications) is that the history of media teaches us that while a technology like AR provides a set of features that can be exploited (what we in HCI would call “affordances”), the useful forms for a new medium emerge through use. Media forms can be thought of as sets of conventions that can be used by developers to create meaningful information experiences for consumers, and the tools used to work with a medium reflect the common media forms. The history of media has also shown that any medium (not just AR) will not reach its potential until it is put into the hands of designers working on their own projects. Consider the evolution of film. The film camera, projection, and distribution system (invented and perfected from about 1890 to about 1930) constituted a new technology of representation but did not define what we think of as “film”. This technology developed into a large number of different film forms over time: the Hollywood narrative film, the documentary, the educational film, and so on. The common structure of modern film forms in turn define the necessary features of digital video editing software, such as Apple’s iMovie. Programs like iMovie, in turn, define the capabilities and experience of most people working with video.

And so it will eventually be for a medium like AR; by working on real projects with motivated content-creators, I am taking the first steps toward defining the tools and processes that will eventually define how vast numbers of people create and experience AR and other mixed physical/virtual experiences. By understanding both the kinds of content that need to be created, and the challenges of working with the medium of AR from initial conception through prototyping and on to final application delivery, we can begin to solve the important problems faced when creating AR systems.

A. Research in Augmented Environments

Various terms have been used to describe systems that combine physical and virtual worlds, such as augmented reality (AR), tangible environments, wearable computing and ubiquitous computing. Each of these terms connotes a specific research agenda and set of interests on the part of their proponents; all focus on integrating computers with the physical world. On one hand, some researchers define their work based on how the computer generated media is integrated with the world: augmented reality enhances the users perception of the world using various displays that are worn or projected onto the environment, while tangible environments augment the physical objects themselves in the users environment. Other researchers focus on where the computers are: wearable computing advocates believe that the user should carry computational devices, while ubiquitous computing proponents seek to embed computers in the world in which the user lives.

My research spans both of these axes. While most of my current research involves wearable AR, I use the fairly broad term computer-augmented environments, or simply augmented environments (AEs), to capture the breadth of my interest in systems that blend physical and virtual worlds, inde-
dependent of the particular approach used. I am most interested in systems where the physical and virtual worlds are intimately related, and believe that the relationship between the physical and virtual environments is what makes AEs different from other sorts of interactive media. These relationships define an AE system, and have far reaching implications for the underlying software architectures, user interface building blocks, and design and prototyping tools for these systems.

I have established two major lines of research in this thread over the past six years: support for adapting to uncertainty in AR/MR systems, and support for designers exploring AR/MR as a new medium for creativity and communication.

The kinds of questions I am pursuing in my research, in conjunction with my students and collaborators, include:

A.1. How will individuals and groups interact with augmented environments?

People are typically unencumbered when inside an augmented environment. In addition to using input modalities such as speech and gesture, AE software relies heavily on implicit input gleaned from user activity (e.g., location, interactions with augmented objects). All of these inputs are necessarily error-prone, and I do not believe we will ever eliminate these errors. Therefore, we have demonstrated interaction metaphors (e.g., in created constrained entertainment experiences [E.2.12][E.2.9] and content structuring conventions (e.g., as structured tours of historic sites and in linear, multiple-viewpoint dramas [E.2.11][B.1.4][E.2.4]) designed to minimize the user input a system requires, thus minimizing both the amount of user interaction and the need for error recovery. We have also been demonstrated display and interaction techniques that minimize misinformation due to registration errors between the virtual and physical worlds (e.g., through error-adaptive augmentations [C.1.1] and interaction techniques that adapt to tracking error in the system [E.2.3]).

In the long run, we hope to understand more about how co-located and distributed groups will interact with each other in AEs. For example, how will people develop a common frame of reference that incorporates shared and distributed physical space and different AE information displays. We are beginning to examine this problem in a variety of contexts: groups of mobile warfighters trying to acquire shared situational understanding, groups of children playing collaborative, distributed AE games (the ARCraft project), and groups of people visiting historical sites (the next step in our Voices of Oakland project [E.2.4]).

A.2. How to enable effective prototyping of augmented environments?

It is well known that substantial progress in any kind of computational tools requires sufficient scaffolding to enable larger communities of programmers to efficiently solve relevant problems. Our research strives to identify and support these needs across multiple domains in AEs and substantially different levels of programming expertise. For example, all AE systems receive information about the physical world through sensors, and all sensors are error-prone. One question we are investigating is how to support programmers in reasoning about the effects of sensor error on the system [E.2.10][E.2.6]. We have demonstrated how programmers can effectively use this information, such as by opting to expose ambiguity to the end user (such as targeting in a military application) or by compensating for the sensor uncertainty (to create a seamless entertainment experience).

Most AE systems contain a mixture of devices working in concert, but it is usually difficult to create systems that seamlessly integrate many different devices. This difficulty, in turn, hampers HCI and systems design research that relies on this collection of devices working together. One result of the Augmented Office project was to develop tools that simplify the integration of many devices, so that many more system prototypes can be explored [B.2.2][B.1.3][B.1.6].

A more significant problem with prototyping AEs is the difficulty of deploying the technology and developing the underlying system intelligence to deal with unconstrained user action and uncertain
sensors. Therefore, we have demonstrated the value of extensive support for Wizard-of-Oz prototyping in AEs, especially for allowing WoZ techniques to be used extensively and iteratively through the design process as technology and system intelligence are added [B.1.1].

At a higher level, we are working with new media designers to create tools that mirror a combination of traditional and novel design techniques for this new medium. We have made great strides in understanding and supporting this emerging design process including enabling designers to experiment with informal content, capture real world staging information while allowing for off-stage development, and evolving a design from a rote script to an interactive experience [B.2.1]. This work is the basis for my NSF CAREER grant.

A.3. What kind of virtual content will be needed for the emerging media forms of AR experiences?

Traditional AE domains typically require very limited forms of content (e.g., simple virtual objects, labels, highlights), but even these simple elements are difficult to design when we consider how they will interact with the physical world. We are designing a toolkit of visualization techniques (for common kinds of content in these domains) that helps the programmers to build systems that adapt their graphical output to changing real-world conditions. For example, we have demonstrated novel techniques for depicting relevant real world features to aid end users in interpreting a misaligned AE display [C.1.1], and techniques for placement of virtual labels and interaction elements near physical objects [E.2.3].

Conversely, new domains, such as dramatic or playful AR experiences (e.g., domestic [E.2.17] and entertainment [E.3.3, E.2.9, E.2.12] applications), will require new forms of content. Therefore, in addition to mining previous media and media forms for guidance, I am actively engaged in understanding the theoretical implications of AEs as a medium for dramatic experiences. We have looked at procedural dramatic experiences in the past [E.2.12], and have explored the notion of single-narrative, multiple point-of-view experiences as a compelling (and practical) alternative to multi-sequential or procedural experiences [B.1.4]. We have most recently demonstrated a mixture of linear narrative with free-form browsing to support tours of historic sites [E.2.4]. One promising thread of research is extending the concept of “presence” from the VR community to understanding the import of experiencing an AE in an historically-meaningful location. We have proposed designing and evaluating the “aura” of an augmented environment to account for the relevant impact of a real-world location or object [E.2.7, B.1.2].

B. Research Method

While each of these questions are interesting in and of themselves, no one of them can be answered in a vacuum. As can be seen from the descriptions above, the problems overlap and the solutions influence each other. For example, the design of a low level software architecture that encapsulates knowledge about the physical world impacts the design of a visualization toolkit for representing augmentations in the face of real world knowledge. Both of these impact the design of authoring tools, which in turn determine (and are determined by) the sorts of application domains we explore. By investigating these components in concert, each provides a context for evaluating the others. For these reasons, my research is centered around domain-specific projects that provide a context in which each of these questions can be asked and answered.

A fundamental requirement for doing this kind of research is to establish deep interdisciplinary collaborations with both researchers and practitioners. Beyond simply maintaining ongoing connections with various domain experts (to inform our research prototypes, I have established serious collaborations with both the design and art community (in conjunction with faculty in the School of Literature, Communication and Culture, and with professional interactive experience designers outside of Geor-
gia Tech), with computational perception and robotics researchers on the other hand (both within the College, and at the Naval Research Lab), and with industrial application developers (within the Food Processing Technology Division of the Georgia Tech Research Institute). Building ties between such diverse communities, and bringing the cutting edge results of one to the other, is vital to advancing the state of the art of augmented environment research. For example, last year I participated in a two-day design charrette to generate ideas for a dinosaur museum to house Project Exploration in Chicago; the two dozen participants were a mixture of architects, theme park designers and other design professionals with experience creating large interactive exhibitions (I was the lone academic, not including the representatives from Project Exploration itself, and was invited because of my work in Mixed Reality). Similarly, I recently led a team of robotics and intelligent systems researchers in a $13 million proposal to NASA, based on my work on adapting to sensor error in AR interfaces. While the project was not funded, this proposal contains several innovative ideas that we are now pursuing with other funding agencies.

Below is a brief list of my major projects and collaborations. I have also included a more detailed description of these projects, and their relationships to each other, as an appendix.

*Four Angry Men* (aka Three Angry Men), a dramatic AR experience exploring single-narrative, multiple point-of-view. This project was our first fully implemented dramatic AR experience, and served as the impetus for the creation of DART (see below), and for many of the novel ideas embodied within DART.

*The Voices of Oakland Cemetery.* Historic Oakland Cemetery, the oldest cemetery in the South, serves as the basis for an ongoing exploration of dramatic and narrative mixed- and augmented-reality tours of historic sites. We have used Oakland as the basis for projects in our AR Experience Design class for the past three years, as well as for the audio-AR research project *The Voices of Oakland*. As with Four Angry Men, my work with design students and faculty has generated many of the novel ideas that we have pursued in our software projects.

**DART.** The NSF-CAREER-funded Designer’s Augmented Reality Toolkit is a manifestation of our investigation into how designer’s think about design in mixed physical/virtual environments. The software itself is a collection of tools built on top of Macromedia Director, the authoring environment for Shockwave content and the de facto standard for multimedia content creation away from the web. This project represents our concerted effort to bring the technology to the “user” (in this case designers, artists and other content creators) and enabling them to work in a new medium with tools they already know. Through our ongoing collaborations, we are beginning to understand how to support good design in mixed physical/virtual environments, and DART is the embodiment of our ideas. While we are focusing on AR experiences with DART, the ideas and approaches we are discovering are equally applicable to a wide range of MR and ubiquitous computing systems; indeed, any system that mixes the physical and virtual worlds. DART is available free for download, and has already been downloaded by over 500 groups and individuals worldwide.

**Augmented Reality for Poultry Inspection.** This ongoing project is a collaboration between my group and researchers in GTRI’s Food Processing Technology Division. Originally a research project investigating how AR technology could solve communication problems on a poultry inspection line in the presence of increased automation, this project has resulted in a design for a laser-projection AR system that could be practically deployed in the relatively near future. We are currently implementing and testing this system on a GTRI shackle line, and hope to demonstrate a prototype to industry representatives this year. I have presented this work at the American Society of Agricultural Engineers Annual International Meeting [E.3.2].

**Kimura.** In the NSF-funded Augmented Office, or Kimura, project, my group (in conjunction with Elizabeth Mynatt’s group) investigated how to effectively use wall-sized augmented surfaces
in an individual office setting and, in particular, how to seamlessly integrate this new technology with current technology. My groups focus is the creation of the infrastructure to allow these sorts of prototypes to be created and evolved.

**OSGAR.** The OpenSceneGraph for AR project is an ONR-funded project investigating how to support the creation of AR interfaces that adapt in the presence of sensor error. In high unpredictable and dangerous environments, where sensors may be damaged and physical structures may change rapidly (or even be destroyed), systems must function in the presence of significant uncertainty. This project seeks to support the creation of systems that can function under such harsh conditions. More importantly, all AR systems will benefit from such infrastructure, from industrial applications that can function in the presence of heterogeneous tracking accuracy, to medical applications where the system can warn the doctors when there are unsafe levels of sensor error. We believe that our techniques will be the cornerstone to the creation and deployment of working AR systems.

**AIBAS.** The Adaptive Intent-Based Augmentation system was started with the same ONR funding as the OSGAR project, and looks at how to use this uncertainty information provided by OSGAR to actually create graphical augmentations that are understandable in the face of error.

**C. Broader Impact**

In addition to playing a major role in the AE research community, my goal is to influence the efforts of researchers and practitioners in related communities through the dissemination of AE tools and the demonstration of novel AE experiences. In particular, I have sought to increase the impact of my research by:

Designing, building and distributing DART: by making our tools freely available, we are putting the necessary tools in the hands of creative individuals who would otherwise be shut out from using it. While our research goal is to study some of these designers and artists to learn more about design in mixed physical/virtual environments, we also hope to push the field of AR rapidly forward by increasing the number of AR projects worldwide. The history of media shows us that it is these people who have the capability to push AR and MR from the lab out into the world, and to discover what the technology is good for and the capabilities needed to make AR systems a reality.

Championing the use of AEs for historic and educational sites: while many researchers in ubiquitous computing have experimented with the use of technologically assisted tours of historic sites, there has been very little work (beyond visual recreation of destroyed sites) in the AR community. We believe that tightly registered media (graphics and sound) delivering dramatic and/or narrative content can be radically more engaging and meaningful that content delivered on a handheld or through linear audio (as is done now in sites like Alcatraz). Toward this end, I have been establishing collaborations with historians and given talks at history conferences.

Enabling the design and evaluation of ubiquitous computing (ubicomp) environments: while DART was initially conceived as an AR design project, and is heavily focused on support these demanding and complex systems, it has become clear that the ideas and techniques we are developing are applicable to any system that mixes physical and virtual worlds, such as ubicomp systems. Perhaps more exciting, we are discovering new uses for AR as we make our tools more widely useful, such as supporting the early design exploration of ubicomp environments and as an interface for human-robot interaction.

Enabling new approaches to human-robot interaction: during the writing of a recent NASA proposal in collaboration with robotics and perceptual interface researchers, we discovered many ways
in which our work on error-based AR interfaces can be applied to HRI and perceptive/gestural interaction. While the proposal was unfunded, we are now beginning to look for other avenues of funding and believe that we will be able to push the area of HRI forward in exciting ways.
Teaching and Education Statement

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One of the main reasons I chose to pursue an academic career, rather than working at an industrial research lab or in a non-research job, is the opportunity to work with students at all levels. I believe that the greatest impact that we have as professors is through the students we teach, either directly (by helping them learn, or by inspiring them to pursue a career or dream) or indirectly (by the impact they have using what they learned from us). I also believe that teaching extends beyond the classroom, and is a core part of all interactions with undergraduate and graduate students; students learn about research by watching me do research, and so on. By thinking about most things I do as a professor through the lens of educating the students I interact with, I find it forces me to be a better teacher and researcher.

Because I enjoy working with students, I encourage them to do independent study projects with me; I supervised over 30 undergraduate independent study projects during my time at Georgia Tech. The goals of these projects were as varied as the students: some wanted practical experience, some wanted research experience, and some wanted to learn new skills (e.g., effective use of modelling tools like 3D Studio Max). My enthusiasm for undergraduate education has also led me to take the lead on designing, implementing and running our new Computational Media undergraduate degree, and to accept a position as one of the two undergraduate coordinators in the College of Computing. I expect that my involvement with undergraduate education will continue to increase.

A. Teaching Philosophy

I focus on two things while teaching. First, I emphasize project-based learning, so my classes tend to have a heavy component of students working on many projects that I try to make interesting and relevant to them; where possible, I try to let the students select projects (or parts of projects) that are interesting to them. Second, I believe that teaching is more effective when the lectures and assignments are interactive, relevant and fun. In addition to having projects that are relevant to the students (as mentioned above), relevancy also means taking time to explain why the material discussed in class is relevant in the “real world”; I try to do this by providing concrete examples of how concepts affect them or others when building or using computer systems. By having the students occasionally work on short assignments together in class, the material becomes more concrete and immediately understandable.

I have been teaching five different classes at Georgia Tech, and use different techniques to accomplish these goals in each class. In my senior undergraduate Computer Graphics class (CS4451), for example, I spent time keeping abreast on the capabilities of current graphics boards and game consoles, and the techniques used in 3D games, and used them as examples in class. This turns out to be especially important, both because it keeps the students interested and because the pace of change means that what was “impossible” to do in real time a few years ago is now available on consumer graphics boards.

To keep classes interesting, relevant and up to date, I try to integrate as much of my own, and others, research into all of my classes. This has a double benefit. First, the students get to see what the cutting edge of technology currently is. Second, my own research is enriched by the constant feedback, reactions and projects of a constantly changing collection of students.
B. Teaching Experience

Before coming to Georgia Tech, I taught a 3rd year Computer Science course at Columbia University called “Software Design Lab.” The goal of this course was to teach practical software design and engineering skills to CS majors; to provide a solid appreciation for how one builds non-trivial software. It was during this that my enthusiasm for project-based learning solidified: for the course to be successful, the students needed to work on projects they found exciting so they would be motivated to do a good job.

Recent Experience. At Georgia Tech, I have been teaching five courses: “Computer Graphics” (CS4451), “User Interface Software” (CS6456, and CS4470), “Building Ubiquitous Computing Devices” (a 1 point undergraduate special topics class, known as “Hackfest”), “Augmented Reality Design” (currently a special topics class, cross listed in CS and LCC, at both the undergrad and grad levels; we expect it to be approved as an official course this fall), and “Introduction to Media Computation” (CS 1315). I have been active in developing the curriculum in most of these classes (all except 1315, which I am teaching for the third time in the Fall 2005 semester). When we switched from 10 week quarters to 16 week semesters, I was responsible for the first semester version of both UI Software (CS6456, formerly CS6395 under quarters) and Graphics (CS4451, formerly CS4390 under quarters). I created the undergraduate version of the UI software class, CS 4470, which I have taught the first two instances of. I have developed, with Jay Bolter, a new inter-disciplinary project course on AR Design.

My focus in Computer Graphics was to shift the class toward interactive 3D graphics. I added material on animation, time-sensitive rendering, real-time shadow algorithms, and so forth, which I find relevant to today's world. Furthermore, I used Java to teach the class, rather than C or C++, because it has clean, platform independent support for dealing with images, windows, input and file I/O.

The User Interface Software class, designed by Scott Hudson when he was at Georgia Tech, was originally structured as a clear summary of the important points of UI tools for 2D interfaces. The shift to semesters let me add six weeks of material focused on exposing the students to the interactive software issues of non-2D, off-the-desktop interfaces: web-based, pen-based, mobile, 3D, AR, VR, and so on. My approach in these weeks was to force the students (and myself) to apply what they now know about 2D interfaces to understanding software tools for these less mature areas. Each semester, I shifted this “new” content around, depending on the interests of the class (gleaned from questionnaires at the beginning of the semester) and what is currently “hot” (e.g., when I teach the course in the fall, I spend time on material that was presented at the UIST conference, which is always in October or November). My experience attempting to synthesize the ongoing research in the “new” areas into concise nuggets has had a significant impact on my thinking in these areas.

The third class I co-teach, with Jay Bolter in LCC, is a cross-disciplinary course on Mixed Reality Experience Design. The goal of the class is to have the students (who are typically a diverse mix of Computing, LCC, Architecture, Industrial Design, and HCI MS students) think about AR from a media and cultural theory viewpoint, and as a technology for location-based experiences, in addition to the usual technology and HCI viewpoints. We first taught the class for two years as graduate seminar, with the focus of the class being on semester-long group design projects. The emphasis was on real-world “design”: the groups had to consider form, function, and context of use. In particular, they had to design their application or experience with explicit consideration given to the limits of the technology. In the four recent offerings of the class, we have included undergraduates and enough technology (see below) to allow the students to build prototypes of their experiences.

In 2002, I was nominated for the Georgia Tech “Outstanding Use of Educational Technology” award for my integration of advance technology in all my classes. My goal is to have students really use this advanced technology, rather than simply reading about it. Over the past three years, I acquired a significant amount of novel technology (approximately $150,000 worth) to enable the students to explore location-aware computing and tangible interfaces in CS4470/6456, and augmented reality in the MR Design class. To support the first, I arranged for a donation of laptops, WinCE devices, and
Cooltown Beacons (small location sensors) from Hewlett Packard as part of a campus-wide equipment donation from HP. To support the second, I have arranged to acquire a set of “Phidgets” (or “Physical Widgets”, a collection of software and hardware research prototypes designed to make building tangible interfaces easy) from Saul Greenburg at the University of Calgary. We are using all of this equipment, plus additional AR equipment (HMDs, trackers, and so on) funded by a grant from the former Dean of the College of Computing, in our MR class, and have made it available to other classes as needed.

The final class I have taught is the “Hackfest” seminar, which is taught each semester by one of the faculty of the Future Computing Environments (FCE) group. I have been involved in the class twice, most recently three years ago, where I taught it alone. The focus of the class that semester was on a combination of mobile computing and augmented reality; the students worked with the all of the technologies mentioned in the previous paragraph, both to learn about them and to help us prepare for their use in other courses.

### C. Teaching Plans

I expect to continue teaching most of these classes at different points, although my focus is shifting toward undergraduates and courses involving non-CS students. Most importantly, in deciding to teach CS 1315 on a regular basis, I have given up teaching Computer Graphics (4451) and UI Software (6456/4470) for the near future. My current focus is on 1315, MR Experience Design and starting this fall, CS 4452 (Human-Centered Computing Concepts). CS 4452 is an introductory CS course, modeled after CS 1315, for graduate students in our Human-Centered Computing PhD program (and other programs at Tech) who have no CS background. This course was taught concurrently with CS 1315 last year; this fall it will be taught as a separate class for the first time.

I have been actively involved in the design of two new degree programs in the College of Computing: the HCC Ph.D. program, and the joint undergraduate program in Media Computing between CoC and LCC. In support of the HCC program, I helped design the graduate computing course required of these students, building on my experience in 1315 (teaching CS concepts to non-CS majors), UI Software (teaching interactive software architectures) and MR Design (teaching design and prototyping).

I was the lead designer for the Computational Media program from the College of Computing. Together with Peter McGuire, from LCC, I designed the degree program and managed the process through to its approval. I am now serving as the Faculty Advisor for the program for the College of Computing (in conjunction with Peter McGuire and David White, the CM academic advisor).