Technology and Tools to Enhance Distributed Engineering Education

Georgia Tech provides remotely-located students with classrooms that feature live lectures with face-to-face interaction and discussion between students and instructors.

By Ghassan AlRegib, Member IEEE, Monson H. Hayes, Fellow IEEE, Elliot Moore, II, Member IEEE, and Douglas B. Williams, Senior Member IEEE

ABSTRACT | While the ongoing information technology (IT) revolution is providing us with tremendous educational opportunities, educators and IT researchers face numerous obstacles and pedagogical questions. The Georgia Institute of Technology (Georgia Tech) has a long history in engineering education research and has developed and designed many different tools for instructor authoring, course capturing, indexing, and retrieval. Special attention has been applied to the design and deployment of distributed learning environments. This paper describes the environment and challenges facing Georgia Tech as it expands its campus worldwide while maintaining integration of faculty and students across these campuses. The focus is primarily on the problems of synchronous delivery to multiple sites with a description of how technology is currently being deployed in Georgia Tech’s distance-learning (DL) classrooms, as well as technology that is under development for the DL classroom of the future.

KEYWORDS | Concept maps; digital ink; distributed learning; education; engineering education; immersive technologies; multiarray imaging; shared reality; Tablet PC

I. INTRODUCTION

Founded in 1885, the Georgia Institute of Technology (Georgia Tech) spent its first hundred years within the city limits of downtown Atlanta. The school’s second century has seen a rapid expansion of its research and degree programs to other locations, including Savannah in southeast Georgia, Metz in the Lorraine region of France, and Shanghai in China. In addition, Georgia Tech offers graduate and continuing education courses that are available remotely to students wherever they may be. The concept of a “distributed campus” has been a key component of Georgia Tech’s geographical growth. Rather than operating distinct, largely independent campuses, Georgia Tech has adopted the idea of a single distributed and integrated campus where students and faculty within a particular school or college may be located in different geographical locations. Many other university systems have a distributed campus network, but what makes Georgia Tech unique is the integration of the campuses. All academic procedures, including faculty hiring, faculty meetings, graduate student recruiting, and collaborative research, take place transparently across campuses. Students at any campus have the option of remotely attending various seminars and talks utilizing the distance-learning infrastructure between campuses. Students have the option to study, conduct research, and work together even if they are geographically located at different locations. Similarly, faculty members on a doctoral thesis committee can be based at any campus, and they can participate in the dissertation defense using the distance-learning infrastructure and technologies. Such a model for an integrated network of campuses would not be possible without educational technology for teaching, research, and collaboration. As noted in The World is Flat, Thomas Friedman writes: “What the Georgia Tech model recognizes is that the world is increasingly going to be operating off the flat-world platform, with its tools for all
kinds of horizontal collaboration. So schools had better make sure they are embedding these tools and concepts of collaboration into the education process” [1].

With this infrastructure and vision, Georgia Tech has been working on developing cutting-edge technologies that serve the mission of a global multicampus institute. Such technologies are recognized to be essential in educating future engineers, as noted in the National Academy of Engineering report “Educating the Engineer of 2020,” which states that such technologies will enable the “sharing of ideas, materials, and other resources relating to the transformation of individual courses or labs, departments, programs, or institutions” [2].

This paper shares Georgia Tech’s experiences in technology-enhanced engineering education and discusses the vision of the technology that will enable students within a distributed campus to have a rich and engaging learning environment. Although Georgia Tech has a long history of innovation in asynchronous course delivery through its Distance Learning and Professional Education (DLPE) department, as well as a successful research program in the development of authoring tools, technologies for course capture, and tools for indexing, searching, and content retrieval, this paper focuses on issues related to synchronous course delivery across a distributed educational system that spans the globe. Specifically, the scenario that is addressed is one in which students at a remote site view the lectures live and have the ability to participate in the class as if they were in the same classroom with the instructor. This paper first discusses the challenges that face developers of educational technologies for this modality of educational delivery and then describes the current environment at Georgia Tech that supports synchronous educational delivery. This paper then discusses some of the technological and engineering components that are in the experimental phase at Georgia Tech. It also addresses the primary obstacles that face technology developers for engineering education in a distributed environment. Before describing the technological aspects, a background on Georgia Tech’s multicampus structure is presented.

II. BACKGROUND

With Georgia Tech now in its second century, it finds itself structured as a multicampus institute with academic and research units in many parts of the world (Fig. 1). For example Georgia Tech Lorraine (GTL) in Metz, France, was launched in 1990 as Georgia Tech’s platform in Europe. GTL currently offers Georgia Tech graduate degrees in electrical and computer engineering, mechanical engineering, and computer science. Double degree programs, leading to the master’s of science from Georgia Tech and a graduate diploma from one of the seven French

![Georgia Tech Global Campuses and Units](image-url)
Asynchronous delivery of courses to Metz as current delivery system. GTL has just begun to experiment with the process of capture, zipping, and sending the lecture files electronically. Initially, the process of capture, zipping, and sending the lecture files by file transfer protocol was manual and time-consuming but was later replaced with a fully automated capture and delivery system. GTL has just begun to experiment with synchronous delivery of courses to Metz as current technology and tools now enable and support such delivery.

Another international program that was recently launched is one in Shanghai, China. In partnership with Shanghai Jiao Tong University (SJTU), selected Georgia Tech graduate courses are taught at SJTU by Georgia Tech faculty during the summer and fall semesters of each year. Through the GT-SJTU dual degree program, students at SJTU can earn a master’s degree from each institution: a non-thesis master’s degree from the School of Electrical and Computer Engineering at Georgia Tech and a thesis master’s degree from the School of Electronic, Information, and Electrical Engineering at SJTU. Georgia Tech Shanghai also accepts a limited number of students from outside of China who will only pursue the Georgia Tech master’s degree in Shanghai. Currently, all courses are taught live at SJTU by Georgia Tech faculty. However, it is possible that, in the foreseeable future, courses will be delivered synchronously from Atlanta to Shanghai and vice versa. Perhaps the biggest challenge in this endeavor will be the 12-hour time difference between the two locations.

A slightly different type of Georgia Tech operation has been launched in Athlone, Ireland. In 2006, the Georgia Tech Research Institute (GTRI), the applied research arm of Georgia Tech, established a research enterprise in Athlone to focus on industry research and development needs. GTRI Ireland is GTRI’s first applied research facility outside the United States. Over its first five years, the Irish operation plans to build up a portfolio of research programs and collaborations with industry, and at full operation it will employ 50 highly qualified researchers. The institute works closely with Irish corporations and universities, the Georgia Tech research community, and U.S. companies to provide companies on both sides of the Atlantic with industry-focused research and development that bridge the gap between academic discovery and commercial success.

Another Georgia Tech unit that contributes considerably to Georgia Tech’s mission as a global institute is DLPE. DLPE provides high-quality support for lifelong learning opportunities delivered with exceptional customer service to the global community in a financially sustainable way. Besides offering professional education courses and certificates, DLPE also captures and encodes all distance-learning courses for video-on-demand so that a student is able to view the lecture on the Web, anytime and anywhere, at his or her convenience.

Nationally, Georgia Tech has two campuses within the State of Georgia: the main campus in Atlanta and the Savannah campus in southeast Georgia. Georgia Tech Savannah (GTS) evolved from the Georgia Tech Regional Engineering Program (GTREP), a state-funded initiative that began in 1999 in which students from regional partner institutions transfer into the Georgia Tech engineering program during their junior year. Unlike a traditional transfer program, such as Georgia Tech’s Regents Engineering Transfer Program, where students physically relocate to the host institution, GTREP students have the option to remain at their home institution and take Georgia Tech classes (except laboratory classes, which must be taken at GTS) by distance learning from either Savannah or Atlanta. Georgia Tech Savannah has established partnerships with three diverse public universities in the State of Georgia who design freshman and sophomore curricula to provide the necessary preparation for students to transfer into the Georgia Tech engineering program. These regional partners are Armstrong Atlantic State University and Savannah State University, which are located in Savannah, GA, and Georgia Southern University, which is located in Statesboro, GA, approximately 50 miles from GTS (Fig. 2).

The initial focus of GTREP was in southeast Georgia, and the mandate was to deliver a Georgia Tech education to an expanded student body with no loss of quality and with no compromise on standards. The admission process, educational requirements, and degrees awarded by the program are all the same as those for students who would transfer directly to the Atlanta campus. With the growth of its graduate and research programs, GTS now finds itself expanding beyond the initial three partner institutions and is attracting students nationally as well as internationally.

GTS currently consists of three state-of-the-art research and classroom buildings, and offers undergraduate and graduate degrees in four engineering disciplines: civil engineering, computer engineering, electrical engineering, and mechanical engineering. GTS and GT Atlanta are fully integrated and operate as a single institution. For example, faculty in Savannah are Georgia Tech faculty and report to the school chair in Atlanta. Faculty hiring along with faculty reappointment and tenure decisions are made by committees with faculty representatives from both campuses. Students, and sometimes faculty, flow between the campuses. To complete the integration, faculty at either campus teach classes to students at both campuses.
Graduate courses, for example, may be taught by a faculty member in Savannah to a class with students only in Atlanta, or with students in both Savannah and Atlanta. The same also occurs in reverse, with faculty having courses that originate in Atlanta and are delivered to students in Savannah. To facilitate this connection of faculty with students, the two campuses are connected via a 10 Gbps fiber connection.

While serving the educational needs of southeast Georgia and beyond, GTS also serves as the experimental testbed and the research and development hub for distributed engineering education. The technology and teaching pedagogy for distributed learning that are being developed, tested, and deployed at GTS serve as a model for distributed learning at Georgia Tech campuses worldwide. The remaining sections of this paper describe the evolution of Georgia Tech’s synchronous distributed learning program, present some of the technologies and pedagogy in distributing courses across a campus network, and provide a vision for how Georgia Tech is working to build the future distributed classroom for a multicampus institute.

III. DISTRIBUTED LEARNING AT GEORGIA TECH

To realize the multicampus vision described above, Georgia Tech emphasizes innovation in engineering and technological systems that enhance distributed engineering education. Not only is research in engineering education at Georgia Tech a priority, but it also is one of the recommendations in a report prepared by the National Academy of Engineering that states, “Colleges and universities should endorse research in engineering education as a valued and rewarded activity for engineering faculty and should develop new standards for faculty qualifications” [2].

In this section, the challenges facing educators in effectively delivering classes in real time to students at geographically different locations are discussed. Furthermore, the current environment for distributed engineering education at Georgia Tech is described.

A. Challenges

When students are distributed across multiple campuses, there are several important challenges for effective delivery of courses and educational content. Among all the
challenges, we believe there are three that must be addressed to enable an effective synchronous delivery of classes.

1) **Constraints on Teaching Style**: Here the goal would be to design a distributed-learning classroom that removes any restrictions or constraints on teaching style and pedagogy.

2) **Loss of Student Connectivity**: The environment for the student who is removed from the live classroom should not become detached or be neglected.

3) **Limited Engagement Opportunities**: In the ideal distributed-learning classroom, technologies and tools would provide a rich set of choices for student participation and engagement.

**Constraints on Teaching Style**: In classroom environments where bandwidth and infrastructure are limited, it may not be possible to support all forms of teaching styles, thereby compromising the effectiveness of some instructors. For example, instructors whose teaching style is free-form lecturing on a whiteboard often are not well suited to a distributed classroom environment. Limited video resolution requires that the instructor write legibly and in a font sufficient for capture and/or delivery. Another issue, which in some cases is more constraining than the first, is that unless there is a conscious effort to write in an organized manner, the video camera may not be able to capture or follow the whiteboard choreography of the instructor. For example, the instructor is not as free to move around from one board to the next, or to point to equations or illustrations outside of the view of the camera without making it difficult for the far-end students to follow. As a result, effective delivery may require that the instructor lecture from pre-prepared electronic material, such as PowerPoint, or lecture within the confines of a Windows Journal environment or a pad of paper that is captured with an overhead camera. In any of these environments, however, attention must still be given to the size and clarity of the written text and equations.

**Loss of Student Connectivity**: Another issue is what might be called the *computer screen hypnosis syndrome* that one experiences when viewing a computer screen or high-resolution monitor at the front of a classroom for long periods of time. When a computer screen or the content captured from an overhead camera or zoomed-in text on a whiteboard is the only thing that a student sees at the far-end sites, it is easy for the student to become disconnected and feel detached from the instructor and the class. Although one may consider having a facilitator in the classroom who periodically changes the view from the computer screen to the instructor who is lecturing, this adds additional costs and has its own inherent problems, such as determining when the appropriate time is to divert the students attention away from the electronic whiteboard to the instructor.

**Limited Engagement Opportunities**: Even when high-quality audio and video are transmitted seamlessly over the Internet, the instructor is faced with the challenge of promoting student participation and engagement of students at the far end. Unless there is a reverse video feed from each of the far-end sites, with a very large video display that allows the instructor to feel that these students are a part of the classroom, they will often be forgotten. While it is often difficult to get students in the live class to participate in classroom discussions, it is even more difficult and challenging to engage the remotely connected students. In the live class, for example, it is a simple task to pose a problem to the class and then have a student come to the whiteboard to work out a solution. This, however, is not possible for the far-end student. In the live class, it is also very easy to assess students with a poll or short quiz, but without a proctor or person at each of the far-end sites, this is not easy to accomplish in the distributed-learning environment.

**B. Distributed Education at GTS**

1) **Live Course Delivery**: The first-generation distance-learning system implemented to support the GTREP program before it evolved into Georgia Tech Savannah followed a conventional design paradigm. Distance learning for the remote classroom was supported by the Georgia Statewide Academic and Medical Systems network, which is based on the H.320 protocol and dedicated T1 lines. This network provided a means for a video and audio channel to be carried to remote locations for the purpose of live interaction. Such systems are characterized by a single “TV”-channel mechanism, forcing all of the live content to fit into a standard video stream. When the resolution and quality of the video channel were insufficient, this could be supplemented by Web, fax, or physical mail delivery for additional material. These systems generally were used in the context of a central origination site and remote receiving sites, with limited “key-the-mike” style interactions to accommodate (but rarely encourage) student questions.

While this system leveraged a huge distance-learning network with more than 300 sites, this technology was a limiting factor for distributed education and learning since scheduling required at least 48 hours notice; and, more importantly, sites were confined to large and costly classrooms with prewired and dedicated T1 lines.

The next generation of systems at GTS was designed with educational delivery in mind. However, in this design, Georgia Tech has faced a unique challenge in having engineering students distributed across multiple campuses, and with faculty moving from one site to another to deliver courses. Georgia Tech Savannah utilizes academic facilities at the three regional partner campuses, the GTS campus, and the Atlanta GT campus to educate its engineering students. Lecturers are presented live from...
one site with real-time video feeds to other sites. This real-time interaction often involves multiple sites at multiple campuses. Therefore, the instructor faces a unique challenge in the GTS teaching scenario as (s)he rotates between classrooms from lecture to lecture. Ideally, an instructor would be able to make a presentation from any classroom at any site without any modifications. For example, if an instructor has students at three campuses who are participating in the class at the same time, then it should be seamless to be able to lecture from any of the three classrooms and have access to the same facilities and format, regardless of which site is used for the live presentation. To facilitate this, GTS has successfully identified, tested, and deployed a prototype baseline classroom or, more explicitly, a standard “distributed education” classroom.

For the last five years, the standard has been undergoing improvements and refinements. Sites have been comparably equipped so that the lecturer can rotate among the participating locations, changing the source of the live lecture without requiring any changes to the presentation. However, the current system is not perfect. For example, it consists of a single video feed that may be switched by an in-class facilitator between a video feed showing the instructor and a video signal showing the output of an overhead camera or a scan-converted computer screen. Ideally, each student would have independent control of the feed that is being viewed. An even better solution would be to have multiple feeds that are delivered to each site so that the student at the far end can direct his/her attention to the channel that (s)he is interested in. One affordable solution that is easily deployed, and one that Georgia Tech is currently using for some of its classes, is the H.239 protocol that allows for the simultaneous delivery of a data stream along with a separate video channel. This enables one to display a video of the instructor along with what is being displayed or written on the computer screen. Carrying this to the extreme, one can envision the recreation of the classroom using a camera array at the near end and a video wall at the far end. However, at this point in time, such an environment pushes the envelop of today’s technology and current university budgets. More will be said about this and other future technologies in Section V.

2) Online Course Delivery: In early 2000, Georgia Tech offered its first online, continuing education course, which was entitled “DSP for Practicing Engineers” and covered both introductory digital signal processing (DSP) and real-time programming [5]. Since that time, this course has been offered three times a year to class sizes ranging from five to 60 students. The target audience for this course is engineers and programmers with bachelor’s or master’s degrees who are working in industry with little or no knowledge of DSP but with some experience using microprocessors and the C programming language. The 14-week course is composed of three interconnected tracks in DSP system theory, real-time implementation principles, and laboratory assignments with MATLAB and the latest Texas Instruments (TI) DSP microprocessors. It is intended specifically to provide a full semester’s course in a way that is adapted to the schedules and circumstances of practicing engineers.

Since its first offering, many changes have been made to this course, largely in response to feedback from students. One specific example of this process involves student interaction, with each other as well as with the teaching staff. In any course with a significant laboratory component, many students require assistance in order to get their hardware and software to work, but with an online course it can be a challenge to provide this assistance. Most of the necessary interaction has been achieved via a very active course bulletin board, where students are able to answer each others’ questions and to get input from the instructors. The majority of the staffing for the course is also focused on the lab requirements and the need for quick, accurate responses to the students.

In the beginning, the workhorse of this course was the inFusion software package [6]. The purpose of inFusion was to simplify and automate the generation of online lecture modules at a time when such packages were not commercially available. InFusion is a presentation synchronization tool that significantly decreases the online lecture module construction time, making it possible for an instructor to create lecture modules without assistance. Presentations can be created at home or in an office, classroom, or studio. Almost any Web-viewable graphics can be used, so existing presentation materials can be made into new online presentations. Ease of use, flexibility, and low cost are all key to engaging faculty in the online content creation process and, as a result, improving the quality of the final product.

For the “glue” that ties together all of the course content, the commercial course Web site software WebCT® has been used. This interface provides the following functionality.

- **User Login:** The ability to connect to the course site from anywhere on the Internet yet also restrict access to only those students registered for the course.
- **Bulletin Board:** Allows the posting of notices and course information, and enables asynchronous student–instructor and student–student interaction.
- **Quizzes:** Contains built-in tools for online quizzes, including automatic grading. This feature is useful both for periodic quizzes and for self-test questions to check a student’s comprehension of each module.

Progress Tracking: Students can see their scores for labs and quizzes. Also, instructors can track how many lessons each student has finished.

“DSP for Practicing Engineers” is by no means a static course. The lab assignments are changed for almost every offering to both improve the labs and address hardware and software changes. With the discontinuance of the ’C6211 DSP Starter Kit (DSK), the course was then offered with the ’C6711 DSK and is now taught using the ’C6713 DSK. Also, a second version of the course based on the ’C5x processor family has been offered, using the ’C5402 DSK in 2001 and, more recently, the ’C5416 DSK. TI’s Code Composer Studio, the integrated software development environment for these processors, has also progressed significantly in the past seven years, necessitating corresponding changes in the labs.

A key aspect of this program is the continued development of tools for the construction and delivery of these courses. Perhaps the greatest impact of this program, however, is the use of these tools in other aspects of Georgia Tech’s curriculum, including:

- the electrical and computer engineering (ECE) degree programs, where content originally prepared for online delivery is used to enhance on-campus courses;
- the ECE remote master’s program, where there have been several online graduate courses for remote master’s students.

IV. ELEMENTS OF FUTURE DISTRIBUTED-LEARNING ENVIRONMENTS

As Georgia Tech continues its development of the distributed-learning classroom of the future, one that is tailored to its multicampus organizational structure with programs and students throughout the world, there are many issues and challenges that must be addressed. The following two sections describe two of the components that we believe will be important to the success of this classroom. The first is digital ink technology with tablet PCs that will enable faculty to deliver high-resolution educational material, including lecture notes, directly to the students desk while allowing for live and interactive dialogue with students locally and remotely. The second is an online resource of concept maps, problems, and Web-based content that may be used within the classroom for testing and assessment of student learning or at home by the student to assist him or her in building an understanding of course concepts.

A. Digital Ink Technology

The integration of technology and learning should be seamless and allow instructors and students to create an environment where ideas are freely expressed and unhindered. To fully address this, it is necessary to consider the core of effective learning and instruction. The process of information delivery in a traditional classroom generally involves an instructor presenting written or electronic material while the students process and/or write down the information presented to them. In addition, instructors may pose questions and present problems or exercises to the class with the goal of promoting student engagement and interaction and creating an environment that leads to a deeper understanding of important concepts. It has been widely acknowledged that effective educational practices should provide active learning environments in which the cycle of knowledge transfer between instructor and student involves feedback to correct misconceptions and promote student learning. Educational research has established a sound set of principles to better understand the paradigm of human learning [7]. As noted earlier, distributed-learning environments present very real challenges in effectively meeting the core requirements for promoting active learning. A particularly damaging limitation to traditional distributed-learning environments that further elucidates these challenges is the difficulty in producing learning material “on-the-fly.” Engineering and other related areas of science and technology rely heavily on the presentation and creation of complex equations, diagrams, rough concept sketches, and practice exercises between the instructor and students. In some instances, an instructor can prepare all of the learning material needed for the class prior to lecture. However, with an active flow of learning, it is very likely that interaction with students will prompt questions and lead in directions that are not anticipated and cause a good instructor to reorganize the intended lecture to properly address and test the needs of the class in “real time.” This exchange is largely limited to verbal interaction in traditional distributed learning environments, which can hinder or completely halt any kind of spontaneous learning exchange. It is therefore also important to address technology that supports electronic content sharing and creation in distributed environments. With NetMeeting software, Microsoft was an early adopter of the ability to share and create electronic documents during collaborative sessions. The original premise of NetMeeting was based on business applications where document creation consists primarily of predefined figures, numbers, and/or text for which a standard mouse/keyboard input modality is generally sufficient. However, the mouse/keyboard input modality was designed for enabling clean and professional content presentation and not for live content creation, making it considerably less useful for creating spontaneous material in a live class session.

Digital ink technology has added another input modality, allowing instructors and students to treat computer screens as electronic whiteboards. The use of digital ink in the classroom is not entirely new, as electronic whiteboards\(^2\) and other forms of digital ink have been

available for a number of years. Digital ink technology has provided flexibility to instructors in creating lecture content before, during, and after class. It has also been shown that digital ink may be used to create annotations on prepared lecture content as a substitute for physical gestures to highlight context and meaning during lecture [8], [9]. Several software programs, such as Classroom Presenter3 and DyKnow4 [10], emphasize the use of digital ink for promoting sound educational practices [11]–[27]. However, while digital ink technology is a wonderful benefit for traditional classrooms, it is absolutely essential for building effective distributed-learning environments. In this spirit, an attractive technology for distributed-learning environments is the Tablet PC [28]. Tablet PCs function in much the same way as traditional laptops with the added functionality of providing the user digital ink as an input modality for content creation directly on the tablet screen. Graphics tablets (a peripheral where the user writes on a pad while viewing the results on a separate screen) may also be connected to standard laptops to provide a form of digital ink input. However, it has been observed that students tend to prefer writing directly on a tablet screen [29], as it is immediately clear exactly where the ink strokes are produced and more accurately reproduces the more traditional task of creating content with a pen. Aside from the digital ink capabilities, Tablet PCs are also of particular interest in learning environments at GTS because of their mobility. Instructors and students may carry a Tablet PC to any learning environment and take advantage of the digital ink modality.

With the support of Hewlett Packard through their HP Technology for Teaching Grant Initiative and the support of Microsoft through the Tablet PC Technology program, Tablet PCs are currently being evaluated for use in engineering courses at GTS. Several distributed learning classrooms have been outfitted with HP and Toshiba Tablet PCs so each student will have access to DyKnow during the lecture. Additionally, several instructors have been provided HP Tablet PCs for use in preparing and delivering lectures. To facilitate shared content between the instructor and students, the DyKnow software program has been installed on all Tablet PCs. The DyKnow software provides an Internet medium through which learning material can be freely exchanged between the instructor and students. Any learning material the instructor desires to present through DyKnow is presented directly on the Tablet PC screen of the student in an uncompressed format, addressing issues with pixel resolution and video quality. Also, any student can create content on their Tablet PC and send it to the instructor Tablet PC for evaluation. The combination of the digital ink capabilities of the Tablet PC and the shared learning space created by the DyKnow software serve to address in some way each of the challenges in distributed-learning environments mentioned above.

1) Addressing Constraints on Teaching Style: The use of prepared lecture material (e.g., PowerPoint) is common in many engineering courses. However, many instructors still feel more comfortable with producing lecture content during class (e.g., writing on a whiteboard). Each of these teaching styles has its own merits and challenges. Preparing slides beforehand can be time consuming but allows for a crisp presentation of material that can be electronically stored and archived. However, once prepared, there is little opportunity to change, annotate, or highlight information during class. Writing on a whiteboard has the advantage of being less constraining than a pre-prepared presentation but can have problems with resolution in a distributed-learning setting. Additionally, even if resolution is improved through alternative technologies, students are forced to copy everything that an instructor writes down or the information will be lost. At GTS, the combination of DyKnow and Tablet PC technology allows for a “hybrid” look at presenting a lecture. In this case, an instructor can prepare as many or as few slides as desired for lecture in DyKnow. Slides can be annotated and highlighted during lecture, or created completely in real time. An example of this concept is presented in Fig. 3. The figure shows a slide that was prepared with some electronic text as an introduction to a new concept. However, the instructor then uses the remaining parts of the slide to write out content related to this concept. Additionally, the instructor has written annotations on the slide to highlight certain key points.

![Fig. 3. Hybrid slide (prepared text and digital ink).](http://www.dyknow.com/)

---

4http://www.dyknow.com/.
being made during the lecture. This “hybrid” view of
lecture creation and presentation is extremely helpful because it provides instructors with more control to choose the style of teaching that they prefer rather than being limited by the constraints of distributed-learning environments.

2) Addressing Loss of Student Connectivity: A very helpful part of dealing with students in distributed learning is to create an illusion of continuity. Students should feel like they are a part of a larger whole rather than an isolated section. An advantage of the DyKnow/Tablet PC combination is that the instructors’ lecture material never needs to be sent over a dedicated link to remote students. While this is not an issue for the H.239 protocol, which allows dual feeds, most of the distributed environments in full implementation across a wide network allow only a single stream (i.e., either the instructor or electronic material). Since the DyKnow software displays the instructor’s content directly to the students Tablet PC, a single video link in distant learning classroom may be used to transmit video of the instructor. The students’ ability to see the instructor as they speak and make physical gestures related to lecture can be very helpful in keeping a “human face” on their instruction. The illusion of being part of a larger whole is further enforced by the ability to conduct polls with the DyKnow software. During lecture, it is common for the instructor to poll the class for feedback. The example in Fig. 4 shows a pie chart that is the result of a class poll for a question relating to the slide. The students’ responses are anonymous and do not require raising hands or verbal response (which are difficult enough to solicit in a traditional classroom and even more difficult in a distributed classroom). Additionally, each student can see where their thoughts and views fit with the entire class, including those with whom they cannot directly interact at the remote locations. The instructor also has the option to solicit an anonymous response to the question “Do you understand?” through the DyKnow interface. Each student can respond anonymously to the professor by selecting one of three options (understand, understand a little, don’t understand), and the results for the class are presented only to the professor. The goal of these types of activities is to help the student feel a connection with the instructor and all of the students in the class.

3) Addressing Limited Engagement: The combination of the Tablet PC and DyKnow software is ideally suited for creating options for directly engaging the instructor and students in shared activities. Of particular interest in engineering disciplines are practice problems, shared diagrams, and other types of technical content that would be difficult to create “on-the-fly” without the proper environment in a distributed classroom. Fig. 5(a) and (b) shows an example of an instructor interacting with the class on a practice problem. In this example, a problem was presented to the class through DyKnow, and each student was required to work the problem on his/her Tablet PC. While this particular example involves numerical analysis and computation, it should be clear...
that this capability to pose questions or problems to students could be applied in a number of ways that are limited only by the imagination of the instructor. After the students work the problems, they submit their responses to the instructor. The instructor can view each student’s response on the Tablet PC and then assess which students are having problems. In Fig. 5(a), the student has answered the problem incorrectly. The instructor can then show the class this incorrect response without revealing the identity of the student who submitted it. The figure shows how the instructor clearly indicates where the error has occurred, and this becomes a point of discussion in the class. After the discussion, the professor chooses a correct response to show the class, as seen in Fig. 5(b). Upon showing the correct solution to the class, various verbal remarks and interaction across the remote sites.

B. Concept Maps, STEPS, and CAPTOR

Having an effective and engaging distributed-learning environment requires more than just technology, high bandwidth, and large video monitors. For example, as discussed in the previous section, Tablet PCs can bring the student in a distance-learning classroom to a virtual whiteboard, and they may be used in creative ways to assess and evaluate student learning. Another way to create a rich learning environment is through the use of tools that may be used within the classroom or outside of class. Several tools that have been developed at Georgia Tech to help students grasp and understand engineering concepts revolve around the use of concept maps. Since one of these tools, CAPTOR, is targeted for use in a distributed-learning environment as well as a more traditional classroom, in the following section discusses how Georgia Tech is using concept maps in its engineering classes and then briefly describe the design goals of CAPTOR. First, a look at how concept maps may play a role in education and the learning process is presented.

1) Concept Maps: The human brain processes information that it receives from various senses and tries to make meaning out of these inputs. In the case of vision, the brain’s task is sometimes simplified if information is presented in a graphical rather than in a textual format. Concept maps are a method of accomplishing this using nodes and links that are labeled to define the relationship between concepts. Thus, unlike an index or a flowchart, concept maps consist of concepts that are linked together to generate propositions. A proposition is usually a semantic unit (a unit of meaning). For example, the concept map shown in Fig. 6 has the proposition: central limit theorem (is an example of) convergence in distribution that links the two concepts central limit theorem and convergence in distribution. Thus, in a concept map, information is presented in a structured graphical format that is easy for the brain to interpret and visualize.

Commercial as well as free programs are available to construct concept maps, such as the concept navigation tool (CNT) developed by the Georgia Tech Digital Media Lab [30] and the CMap Tools developed by the Institute for
Human and Machine Cognition. Both of these tools allow the user to attach resources to individual concepts as illustrated in Fig. 7. These resources include, but are not limited to, Web pages, other concept maps, Java applets, definitions, sample problems, solved examples, images, videos, and interactive media. When a resource is attached to a particular concept, it can be accessed from a menu by clicking a button on the concept. With the addition of resources, concept maps may be used not only to display information visually but also as a tool for navigating resources. The concept maps along with the attached resources offer a rich learning environment for the user.

Extensive research has been done in the area of understanding concept maps and their use as educational tools. Details of this research may be found in [31]–[37]. There are numerous applications for concept maps, including teaching [38], [39], assessing student understanding [35], [40], [41], improved creative thinking [39], brainstorming ideas in educational or business settings [32], and as tools to support the design of instructional material [40]. They can also be used to simplify note-taking, generating various graphics for presentations, lectures, textbooks, etc.

Concept maps are becoming increasingly more important as a learning tool in education. Recognizing the importance of concept maps to facilitate learning and visualization of the relationship between concepts, Georgia Tech has integrated concept mapping into several of its courses, including the sophomore class “Introduction to Signal Processing.” In this course, students, as part of their laboratory activities, are asked to create concept maps using CNT.

2) STEPS: Building upon this idea of embedding concept maps into the engineering curriculum, Georgia Tech has developed a unique problem-centric approach to concept mapping called STEPS that provides relevant concept maps as resources for the user as aids in the formulation of a solution [42]. STEPS was inspired by the recognition that an important aspect of engineering education is learning how to solve problems. Requiring students to solve homework problems outside of the classroom, either individually or in groups, is a common practice used by instructors in science, technology, engineering, and mathematics courses to reinforce concepts that have been covered in lecture. Solving problems within the classroom, either individually or in groups, is a less common practice, but one that can be used effectively to help students learn how to apply concepts to problem solving. Since learning concepts requires knowledge, comprehension, and application, which are lower order thinking skills in Bloom’s taxonomy of intellectual development, whereas problem solving requires analysis, synthesis, and evaluation, which are higher order thinking skills in the same taxonomy, it is not uncommon for a student to have difficulties in associating the appropriate concepts necessary to solve a specific problem, especially when the problem is taken out of context [43]. In other cases, a student may lack sufficient understanding of a given concept to solve a problem.

The STEPS tool was developed to help students learn how to make the association between concepts and problem solving. This was done by using concept maps to facilitate learning using a problem-centric approach [42]. In this program, the student selects a specific concept or set of concepts, the tool searches a database for problems that involve the selected concept or concepts, and the student selects the problems of interest to solve. If the user has difficulty in solving a problem, then the student is presented with the relevant concept map(s). If necessary, the student may also be given some hints on how to solve the problem, but before being given the solution or the answer to the problem, the student must attempt to answer some conceptual multiple-choice questions.

3) CAPTOR: As discussed in the previous section, one of the primary goals of an educator is to introduce concepts to students and teach them how concepts are related to one another. Equally important is to teach the student how to apply concepts to find solutions to new and exciting problems. For an instructor, it is important to be able to measure a student’s level of understanding of concepts as a course evolves, so that if there are deficiencies in student learning, the instructor will be able to address and correct these deficiencies. It is equally important for the student to be able to evaluate and assess one’s own level of understanding of concepts and to be able to practice applying these concepts to solve problems. With these ideas in mind, Georgia Tech Savannah is developing a new tool called CAPTOR that is designed to help students learn how to solve problems, visualize, and understand the relationships between concepts, and provide the instructor as well as the student with an assessment of student learning. As with STEPS, concept maps are the cornerstone of CAPTOR, which uses a problem-centric approach that
allows a student to select problems that require knowledge and understanding of a specific concept along with supporting concepts, which is a useful tool in its own right.

However, the tool becomes more useful and effective when a targeted problem-selection component is attached to the program. By tracking student interactions, logging what problems are attempted, which ones are solved correctly, and what concepts are necessary to solve a problem, a guided problem selection (GPS) tool is integrated into CAPTOR to strengthen application as well as problems that strengthen comprehension. One of the useful and important features of an integrated GPS is that it can select problems to help the student pinpoint what concepts need further study and what specific problems should be worked on to help the student learn how to apply these concepts in problem solving.

The goal is for CAPTOR to provide students with a rich problem-solving environment that is directly coupled to concept maps and managed by the GPS tool. A screen shot of one of the student interfaces is shown in Fig. 8. Another screen shot is shown in Fig. 9, which shows the display of a problem delivered to or selected by the student for a given concept. Although this tool may be used by a student outside of class to test his/her knowledge and understanding of one or more concepts in a course, it may also be used by the instructor as a problem server to students in class, either for discussion or for evaluation of student understanding.

V. FUTURE ENVIRONMENTS
Looking to the future and the emerging innovations in technology, one that certainly raises considerable excitement for the distributed-learning environment is the deployment of immersive technologies. Among the available immersive technologies, this section describes some of the experiences at Georgia Tech with high-definition video, video camera arrays such as the HP FanCamera (see Fig. 10), and virtual reality (VR)-based engineering laboratories.6 Georgia Tech envisions engineering education in the twenty-first century to be truly ubiquitous e-learning that allows students to engage in the learning process where with minimal need for a live instructor even in acquiring hands-on experiences. The following sections describe two cutting-edge research projects in engineering education: video camera arrays in classrooms and VR-based learning in engineering laboratories. These systems assist educators, learners, and researchers in overcoming the three major challenges in synchronous educational delivery: constrained teaching style, loss of student connectivity, and limited engagement choices.

A. Multiarray Imaging
At this time, most video-enabled classrooms lack high-definition video cameras and network infrastructure (fiber links and gigabit switches) to support high-definition classrooms. In this current mode of technology, the

6The current work in deploying HP FanCameras in distant learning is conducted in collaboration with HP Research Laboratories, Palo Alto, CA.
instructor and the students face various challenges. For example, an instructor may have difficulty recognizing remote students’ reactions during lecture. Also, the instructor in a distant-learning class may experience difficulties in having eye-to-eye contact with the remote students because of the lack of high-definition video. Similarly, students at the remote location rely primarily on the facilitator to pan, zoom in, zoom out, and move the camera as the instructor moves from one side of the board to another side. It would be empowering to be able to give each student the option to independently move the camera without affecting the view of other students. Another challenge facing students at remote locations is that they rely on verbal communications in relaying their questions to the instructor. The body language is not fully captured and conveyed to the instructor.

High-definition cameras help the instructor in identifying remote students and observing their reaction. Similarly, high-definition cameras help the students to clearly read the text on the whiteboard. At Georgia Tech, current research is being conducted to experiment with a technology that goes beyond high-definition cameras such as the HP FanCamera (Fig. 10). The FanCamera consists of 24 video graphics array cameras. The captured video from these cameras is composed and mosaicked into one complete video in real time [44], [45]. As shown in Fig. 11, the upper 24 videos are captured by the 24 cameras. These videos are mosaicked into one single video, as shown

![Fig. 11. A video frame captured by the HP FanCamera.](image-url)
in the lower part of the figure. The resulting video is around 8 Mpxels at 30 Hz.

In its current installation in an experimental classroom at Georgia Tech, the FanCamera is facing the instructor’s area (32 by 8 ft). The video is compressed and streamed over the Internet so remote students may receive it on their desktops and laptops. The students are given a personalized view, where each one can independently zoom in and pan to different parts of the videoed area. The user interface is shown in Fig. 12. With this FanCamera, the educational tools are endless. One of the tools being developed is to have an automated tracker of the instructor [46], [47]. In this tool, a marker is attached to the instructor’s pen to enable the camera to zoom in at a reasonable level while the instructor is writing on the board. When the instructor stops writing, the camera will slowly zoom out to view the whole board or alternatively zoom in on the instructor. The camera follows the instructor’s hand all the time unless it cannot recognize the marker at which the camera zooms out to view the entire instructional area. With this super-high-definition video, part of the videoed area can be reserved for a screen that shows the lecture slides.

When the FanCamera is installed to view the students, the instructor will have individual video of each student. Moreover, when a student asks a question, the camera may zoom in to the student and show the student’s face clearly. Such capability will enable the instructor to easily identify the students’ reaction and, therefore, attempt to gauge their understanding. Using eye tracking and a face emotions translator [48]–[54], one could have automated feedback and assessment to the instructor to help him/her efficiently and constructively change the pace and the tone of the material being explained. Experiments found that gaze coordination is essential in having a constructive human-to-human communications and interaction [55].

1) Addressing Constraints on Teaching Style: With the HP FanCamera capturing the whole instructor’s area, the instructor is free to move between various parts of the
board and between the board and the instructor’s desk or slides. The instructor is not limited as in the case when a typical camera is utilized.

2) **Addressing Loss of Student Connectivity:** The HP FanCamera reduces the detached feeling students may experience. The students will feel engaged in the process because they have the power to view what they want to see in the entire instructional area and are not limited by the camera and/or the facilitator. A student has the option of controlling the view using a joystick, keyboard, and mouse (see Fig. 12).

3) **Addressing Limited Engagement Opportunities:** With the view provided by a multiarray camera such as the HP FanCamera, both students and the instructor will feel closer and encouraged to transparently interact with each other. The instructor will have the ability to ask a student at the remote site to answer a question or share his/her idea. The camera could zoom in automatically to the students as he/she starts speaking.

Having such versatile video available to both the instructor and the remote students, there are endless opportunities in creating educational tools and automated classrooms that will be essential component of in distributed engineering education in the twenty-first century. Beside this advanced enabling technology, another very important aspect in synchronous distant learning regarding laboratories is being addressed. In the current model, the students cannot have distant laboratories, especially for disciplines such as civil engineering and mechanical engineering. The next section describes the current research at Georgia Tech in this area and share the vision for future laboratories utilizing shared virtual spaces where all students from all around the globe can come together into one virtual laboratory and conduct an experiment together.

### B. Engineering e-Laboratories

It is true that the Internet allows educators and learners to remotely share documents and data in audio, visual, and text forms, further promoting the growth of human collaborative activities. High-power computing, real-time graphics, and haptics (convening the sense of touch) have spawned revolutionary human–computer interfaces in multiple domains. Such multimodal interfaces (combining three-dimensional graphics, sound, and haptics) have the potential to advance our understanding of concepts and phenomena as well as promote new methods for teaching and learning. Face-to-face interactions in learning often not only involve the transfer of knowledge in the form of text and verbal instructions but also include handling, i.e., manipulation and control, of objects, be it a device or a machine (see Fig. 13). For example, a lecturer may circulate a device to let the audience or students feel and operate it for a better understanding of its operating principles. As is well known in education, this hands-on experience is a critical part of the knowledge-transfer process. Moreover, multimodal environments with haptic feedback have the potential to augment traditional teaching and enhance student motivation, leading to potential increases in retention levels and intellectual stimulation. This becomes critical to distant-learning students in disciplines that require expensive laboratories such as civil and mechanical engineering. Several teams built virtual laboratories for various applications varying from simulations [56]–[65] to medical surgery [66]–[68]. Engineering education and e-laboratories have received researchers’ attention in recent years, which resulted in several systems that enable students to conduct experiments at e-laboratories such as the iLab7 [69]–[73].

At Georgia Tech, a system that captures the above-mentioned criteria has been built. The system has the following key features:

- supports an interactive and a hands-on approach, where students manipulate objects and devices;
- employs dynamic feedback;
- follows a constructive approach that assists the instructor in explaining concepts;
- makes explicit otherwise inaccessible phenomena, where the students can zoom in at the molecular level and observe what really happens behind the scenes;
- constrains students’ productivity by focusing their attention on scientific features of the phenomena rather than accidental conditions;
- provides a safe experimental environment where the instructor can implement scenarios that contribute to the students’ understanding.

---

7http://www.heatex.mit.edu/.

**Fig. 13. A virtual experiment where a student was asked to build a structure using Lego cubes.**
The system consists of hardware (a computer, data gloves, haptics devices, microphone, and head-mounted display) and software (VR space, multimodal interface, and an authoring tool).

The scenario of using such a system can be best described using an example. Imagine that an instructor is preparing an experiment that teaches students how a transmission gear box in a car works. The instructor starts by utilizing the authoring tool to design the experiment the students will perform in the e-laboratory. The instructor uses one of the open-source libraries that are supported by the National Science Foundation CI-TEAM program to put the experiment together. A student will utilize the data gloves and start performing the experiment. The student will apply certain forces on the transmission and observe the torque, the vibration, and other parameters. The student will be asked to assemble the gear box (virtually) using different items to learn the various concepts. If the student does something wrong, the built-in smart agent will highlight the student’s mistake, provide and show instruction on how to do the task right, and ask the student to repeat the task (see Fig. 14). Also, the system has an evaluation tool for each experiment. At the end of each experiment, the tool will send a report on the student's performance to the instructor for evaluation and feedback. The students will learn the physics and the dynamics by feeling, touching, seeing through, and watching from within.

Such advanced systems will lead engineering education in providing students with hand-on experience in the twenty-first century. To make this a reality, research is conducted on topics such as Internet telemicroscopy, smart objects, and micro/macromekinematics tools [74]–[81]. At the same time, a prototype is being built to test the various results [82], [83]. The goal is to have a new capability in universal e-learning, supporting object handling, control, assembling, and manipulation for enhanced hands-on experience on the part of the student without excessive consumption of physical resources. Furthermore, this concept formulates and constructs instructions for automated e-learning, allowing students to engage in learning and gain hands-on experiences, which may be otherwise unattainable.

VI. THE FUTURE

What is Georgia Tech’s vision for the classroom in the year 2020? Will it be cumbersomely equipped with high-tech equipment resembling a newsroom center, or will it be a streamlined highly intelligent environment that is seamless to operate, transparent to the instructor, and a rich learning environment for the student who is enrolled at a distributed university system?

What we believe is essential is to have technology in place that in no way limits/constrains/hinders the instructor to do what he or she does best, whatever the teaching style or pedagogy that he or she is comfortable with. Any technology must be a turn-key system, not requiring setup, and total transparency is a must. Although one might imagine the future classroom as being designed using immersive technologies, outfitted with huge video walls, equipped with ambient intelligence, and being totally interactive between instructor and student no matter where each may be, many will argue that there is no substitute for live, face-to-face interaction and discussion between the instructor and the student. The direction in which technology and innovation in the use of this technology for education will go is not certain. That, in many ways, is what makes research in engineering education so exciting.

Acknowledgment

Many people at Georgia Tech have played a very active role in engineering education, and it would be difficult to list them all. However, the authors would like to acknowledge T. Barnwell for his leadership as Director of the Center for Distributed Engineering Education at Georgia Tech and the role that he has played in supporting and inspiring those interested in engineering education. The authors would also like to recognize R. Abler, J. Jackson, S. Brennan, and M. Lanier for their valuable contributions in many different projects and initiatives, including their innovative work in developing a high-definition video system for distance learning. They would also like to acknowledge the contributions over many years of L. Harvel, former Director of the Digital Media Lab at Georgia Tech who managed and helped architect many of Georgia Tech’s tools for course capture, retrieval, indexing, and searching. Lastly, the authors would like to thank M. Borkar, J. Li, D. Tucker, and J. Parks for their creative work on the CAPTOR system.
REFERENCES


ABOUT THE AUTHORS

Ghassan AlRegib (Member, IEEE) received the Ph.D. degree in electrical and computer engineering from the Georgia Institute of Technology, Atlanta, in 2003.

He joined the Faculty of the Georgia Institute of Technology in 2003 and is currently an Assistant Professor in the School of Electrical and Computer Engineering. His research group is working on projects related to multimedia processing and communications, distributed processing, collaborative systems, immersive communications, and wireless sensor networks.

Dr. AlRegib received the Outstanding Graduate Teaching Award in 2000–2001 from the School of Electrical and Computer Engineering, the Center for Signal and Image Processing Research Award in Spring 2003 and the Center for Signal and Image Processing Service Award in Spring 2003, all from Georgia Tech. In 2008, Dr. AlRegib received the ECE Outstanding Junior Faculty Member Award at Georgia Tech.

Dr. AlRegib is the Steering Committee co-Chair for the Second International Conference on Immersive Telecommunications (IMMERSCOM), 2009. He was the General co-Chair of IMMERSCOM, 2007. He was the Chair of the Special Sessions Program at the IEEE International Conference on Image Processing (ICIP, 2006). He also serves as an Associate Editor of the IEEE Signal Processing Magazine and as the Chair of the Immersive Technologies Technical and Business Unit (TAB) at the Institute for Computer Sciences, Social-Infomatics and Telecommunications Engineering (ICST).

Monson H. Hayes (Fellow, IEEE) received the bachelor’s degree from the University of California at Berkeley in 1971 and the Sc.D. degree in electrical engineering and computer science from the Massachusetts Institute of Technology, Cambridge, in 1981.

He was a Systems Engineer with Aerojet Electro-Systems from 1971 to 1974. He joined the Faculty of the Georgia Institute of Technology (Georgia Tech), Atlanta, in 1981 and is currently a Professor of electrical and computer engineering. Currently, he is an Associate Chair in the School of Electrical and Computer Engineering, Georgia Tech, and Associate Director for Georgia Tech Savannah. He was General Chair of ICASSP’96 and ICIP 2006. Since joining the faculty at Georgia Tech, he has become internationally recognized for his contributions to the field of digital signal processing, image and video processing, and engineering education. He has published more than 150 papers, and is the author of two textbooks.

Dr. Hayes received the IEEE Senior Award in 1983 and the Presidential Young Investigator Award in 1984. He was a member of the DSP Technical Committee (1984–1989) and Chairmain (1995–1997). He was an Associate Editor for the IEEE TRANSACTIONS ON ACOUSTICS, SPEECH, AND SIGNAL PROCESSING (ASSP) (1984–1988), Second Vice President of the ASSP Publications Board (1986–1988), a member of the IEEE Signal Processing Administrative Committee (1987–1989), and Chairmain of the ASSP Publications Board (1992–1994). He is an Associate Editor for the IEEE TRANSACTIONS ON EDUCATION and a member of the Signal Processing Society Conference Board. He has received numerous awards and distinctions from professional societies.
Elliot Moore, II (Member, IEEE) received the bachelor’s, master’s, and doctoral degrees in electrical and computer engineering from the Georgia Institute of Technology (Georgia Tech), Atlanta, in 1998, 1999, and 2003, respectively. After one year in a postdoctoral position, he joined Georgia Tech as an Assistant Professor in 2004. His research areas include the use of digital speech-processing theory and analysis in the classification of human vocal patterns for determining speaker demographics (dialect, language, etc.), speaker characteristics (gender, dimensions, etc.), and speaker state (emotion, stress, etc.). Additionally, his interests in engineering education have involved improving the implementation of technology in distributed education for creating active learning environments. He has received grants from HP and Microsoft to support his research efforts in this endeavor.

Dr. Moore is a member of the IEEE Signal Processing Society, IEEE Engineering in Medicine and Biology Society, and the Acoustical Society of America. He was National Science Foundation (NSF) Fellow, President’s Fellow, and Facilitating Academic Careers in Engineering and Science Fellow. In 2005, he received an NSF CAREER award for the development of new techniques for extracting and integrating features of the voice source into assessing speaker affect/attitude. In 2007, he received a Presidential Early Career Award for Scientists and Engineers.

Douglas B. Williams (Senior Member, IEEE) received the B.S., M.S., and Ph.D. degrees in electrical and computer engineering from Rice University, Houston, TX, in 1984, 1987, and 1989, respectively. In 1989, he joined the Faculty of the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, where he is currently a Professor and Associate Chair for Undergraduate Affairs. There he is also affiliated with the Center for Signal and Image Processing and the Arbutus Center for Distributed Engineering Education. He was an Associate Editor of the EURASIP Journal of Applied Signal Processing. He was Coeditor of the Digital Signal Processing Handbook (Boca Raton, FL: CRC Press/IEEE Press, 1998).

Dr. Williams is a member of Tau Beta Pi, Eta Kappa Nu, and Phi Beta Kappa. He was an Associate Editor of the IEEE TRANSACTIONS ON SIGNAL PROCESSING. He is currently a member of the IEEE Signal Processing Society’s SPTM Technical Committee and Education Technical Committee and has been a member of the society’s Board of Governors. He is Area Editor—Special Issues for IEEE Signal Processing Magazine.