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Signal Processing for the Arts: Reaching Out to New Audiences

Today, *media creators* form a significant fraction of those who use signal processing tools. Environments such Max/MSP [1] and Photoshop [2] play a key role in the creation of music and images. In these environments, authors frequently use advanced signal processing algorithms in the form of filters as well as effects such as sound reverberations and delays. However, most of the people involved in media production do *not* have a math background. The content creators are keen to develop a sophisticated understanding of their tools. This allows them to predict the effects of their creative decisions before experiencing them. It also helps foster an understanding of why certain choices (e.g., size of the convolution kernel) can have a big impact on the final result. It is important to note that the computer music community [3], [4] has played a significant role in broadening the reach of signal processing.

In this article, we describe our experiences with developing a signal processing course specifically designed for students with a background in the arts. The course was developed at the new Arts Media and Engineering (AME) program at Arizona State University.

EXPERIENTIAL MEDIA AT THE AME PROGRAM

AME has a research and educational mission focused on the development of experiential media systems. Experiential media systems are new, complementary models of media computing. In the traditional multimedia computing model (e.g., the creation/consumption of a video), capture, analysis and media consumption are not colocated, synchronous, or integrated. We are, however, witnessing a rapid decline in the cost of sensing, storage [5], computing, and display. Thus sensors (audio, video, pressure, and others), computing, ambient visual and sound displays, and other feedback devices (vibration, light, heat) can now be colocated in the same physical environment, creating a real-time feedback loop. This allows us to develop a rich contextual understanding of human activity, at different scales of time and space, as well as to affect human activity in a radically new way. The goal is to achieve enhanced, user-oriented, and unified physical-digital experiences. These media systems will give rise to a new set of multimedia applications grounded in human activity in the physical world.

The development of experiential media systems requires a community of people focused on the same intellectual effort. Importantly, the knowledge required to effectively work on this problem is fragmented across several disciplines. As we are dealing with a hybrid physical-digital space that concerns media, it is of interest to architects (the design of space), engineers (computational aspects), artists (media creation), and neuroscience researchers and social scientists who are interested in cognitive issues and the practice of space, respectively. At AME, there are four key application areas (health, education, everyday living, and interactive arts) that are the driving force for the development of these new media systems (Figure 1). Over 30 students from a broad range of disciplines [engineering, psychology, education, design, and the arts (music, visual art, theater, and dance)] participate in formalized AME concentrations offered by the program. The concentration model requires that students take one-third of the courses from AME, one-third from the major degree (e.g., electrical engineering), and the remainder as research credits spread across the host department and AME. Each student who participates in the concentration, regardless of their home discipline, is strongly encouraged to participate in one of the complex experiential media systems in development at AME. Their successful participation (particularly for students who do not have an engineering background) means that they become familiar and comfortable with key signal processing concepts that form the basis of media production tools.

WHY NEW PEDAGOGICAL TECHNIQUES?

The development of a course for audiences without a math background (e.g., dance and visual arts) is problematic when teaching signal processing concepts that are firmly rooted in mathematics. Most of the students are sophisticated content creators who were last exposed to mathematics in high school, thus precluding any discussion using calculus. Classical textbooks in signal processing such as [6] are difficult to use in these courses. For example, in [6] the authors spend the initial chapters presenting fundamental concepts regarding unit impulses, properties of systems (stability and causality), and properties of linear time-invariant systems. For a classical electrical engineering undergraduate program, the book is entirely appropriate. However, for audiences used to routinely manipulating filters in content creation tools and experiencing media creation, these fundamental concepts appear to be far too abstract.

Thus, such an audience is more interested in experiencing the results in order

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to learn. Hence, new pedagogical techniques to communicate critical signal processing concepts to new audiences must foremost take into account the audience.

In the past decade, there has been a widespread emergence and adoption of graphical programming environments based on a data-flow paradigm such as PD [7] and Max/MSP [1]. These allow for real-time manipulation of audio and video through signal processing networks. In these environments, one has access to a wide range of signal processing units and can develop simple environments for experimentation. For instance, in learning about basic filters, one can directly manipulate the coefficients and hear the results to gain experience-based insight into how these changes affect the filter state.

METHODOLOGY

In our course, we attempted three innovations: 1) develop the course with a foundation in high-school geometry, 2) make the course experiential, i.e., allow the students to manipulate images and sound to understand concepts, and 3) teach the generalization-specialization abstraction process to make the students understand relationships between concepts. For text, we recommended the book *Who Is Fourier? A Mathematical Adventure* [8], which explains the key concepts in Fourier analysis using a *manga* format (manga is the Japanese term for a comic book). The book was written by people who did not have a math/engineering background.

A GEOMETRIC PERSPECTIVE

A geometric perspective to signal processing makes the key concepts accessible to people who only possess a background in high school algebra and geometry. We began teaching the course by presenting Euclid's postulates and revisiting Pythagorean theorems. This allowed us to discuss the triangle inequality and begin to explain the basic trigonometric functions of $\sin(\theta)$, $\cos(\theta)$, and $\tan(\theta)$. Then, we began to develop the idea of functions in a more generalized setting. Euclidean geometry serves as the natural starting point for exploring the idea of vectors and simple algebraic operations of additions/subtractions as well as scaling.

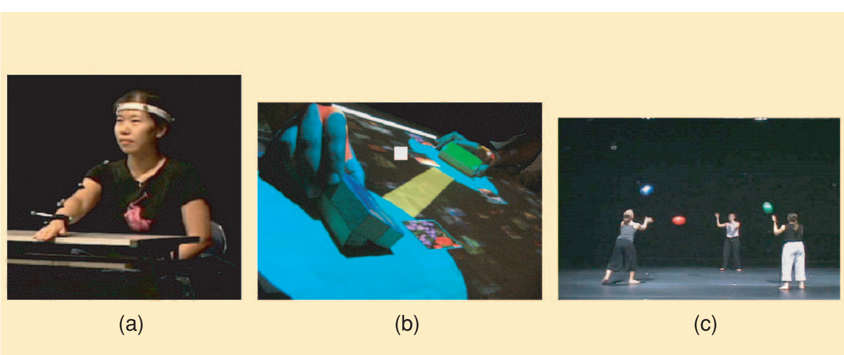
The key concept of a linear filtering process now can be introduced as a projection of the signal (input) onto the filter. A poorly designed filter can cause the interesting (e.g., specific harmonics) data to be lost, as the signal is not correctly projected onto the filter. The students with a geometric understanding readily appreciate the "matched filter" and learn that, unless the filter and the signal are aligned, there is not an optimal transfer of signal energy. Geometric projection of one vector onto another (illustrated using triangles in Figure 2) also allows us to introduce the idea of orthogonality; we show that it is possible to design filters that completely eliminate certain parts of the input. We also briefly introduced the concepts of differentiation by analysis of physical phenomena of movement. Integration was introduced by exploring how people began to measure area by knowing how to measure the area of a rectangle.

EXPERIENTIAL INTRODUCTION TO SIGNAL PROCESSING

It is important to give practical examples that demonstrate applications of the concepts being introduced. For example, we found that the concept of convolution is particularly difficult for our students to understand using traditional definitions. The idea of convolution is typically introduced in undergraduate engineering classes using the impulse response, which in the continuous case requires an introduction of the familiar Dirac delta function.

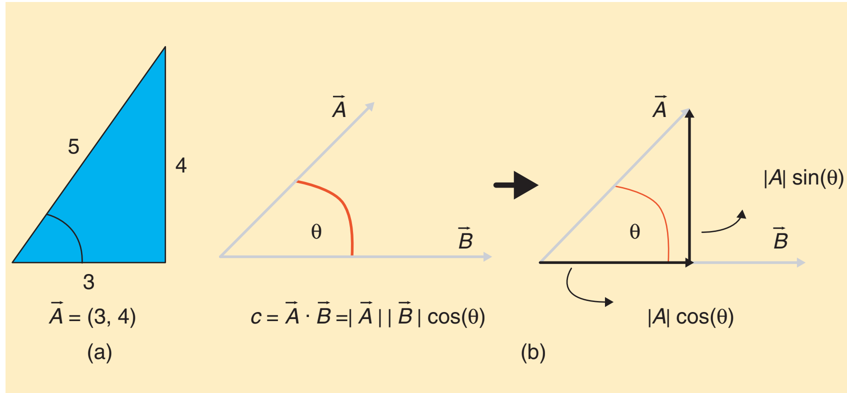
To illustrate convolution we decided to start by adding reverberation to a sound file, which is a typical step in audio production. In our first example, two audio files were played. The first file consisted of a person speaking. The second file contained an impulse response of a large cathedral. We then convolved these two signals to create a third signal, which predictably sounded as if speaking was taking place in the cathedral. This example avoided a common mistake that many students make when they are first introduced to convolution. Trying to make analogies, they erroneously first try to understand it as some type of "cross fading" of two signals, thereby fundamentally missing the implications of the concept.

Properties of a linear system were introduced next using the experiential approach with images and sounds. We explored the concepts of signal additivity and scaling though sound examples. Pure sine tones generated in Max/MSP were played back in class interactively, at every stage making a correspondence with the linear system concept. This approach using sinusoids also allowed us to simultaneously explore concepts of periodicity, phase, and amplitude of sinusoids. Interactively working with sounds is of tremendous value when dealing with concepts of phase, as the consumption of sound is linear (it is also easy to cascade several filters and illustrate the idea of linearity) and phase (the misalignment between sounds is noticed immediately).



[FIG1] Images from three experiential media applications in development at AME (a) biofeedback for rehabilitation, (b) everyday living, and (c) experiential education.

After using the sinusoids, it became natural to introduce the idea of a Fourier series as a sum of many sinusoids that could successfully represent *any* periodic signal. However, in this course we did not discuss some key aspects of Fourier analysis: 1) sinusoids are eigenfunctions of linear time-invariant systems and 2) the Fourier basis form a complete orthonormal set (we discussed orthogoanality of sinusoids, but not completeness). Furthermore, we did not discuss the familiar Z/Laplace transforms. In the context of this class audience, these choices are appropriate.



[FIG2] The two figures show the basic concepts from Euclidean geometry and elementary vector spaces: (a) the relationship between the dimensions of a two-dimensional vector and its magnitude and direction and (b) the visualization of the inner product of two vectors as a projection of one vector onto the other.

SIGNAL PROCESSING CONCEPTS RELATED TO CONTENT CREATION

Since the audience was interested in content creation, it was important to discuss concepts relating to sampling, quantization, filtering, and noise. The audience experienced aliasing phenomena through movie clips that demonstrated the effect of sampling rate on a variable speed strobe. This helped motivate the discussion on sampling frequency and the Nyquist sampling theorem. Through the use of aliasing as an example, we illustrated the dual time-frequency relationships, as well as the familiar concepts of downsampling/upsampling and the role of pre/post-filtering in preventing aliasing. These concepts were demonstrated using audio clips. The discussion on sampling also helped us focus on the role of quantization. Through both images and sound, the effects of reducing the number of bits used to represent the signal were demonstrated and the class experienced the reduction of signal-to-noise ratio (SNR) for both images and sound.

For an audience without a traditional signals and systems background, the discussion of filters is quite challenging. Understanding filter design involves a discussion of numerous concepts, such as rise-time and pass-band ripple, which typically appear to be abstract to such an audience. Some concepts such as the stop band attenuation, the quality of the roll off, and the relationship between filter length and delay are easier to understand, but it is still difficult to explain through examples concepts such as the effect of a nonlinear phase filter on sound.

We devoted some time in the course to concepts related to probability. Our goal was to communicate basic concepts such as independence and mutual exclusion, simple statistical measures of mean and variance, basics of Gaussian processes, and the idea of SNR. We presented the effect of noise variance on media by interactively creating different image and sound clips with different SNRs.

THE GENERALIZATION-SPECIALIZATION PROCESS

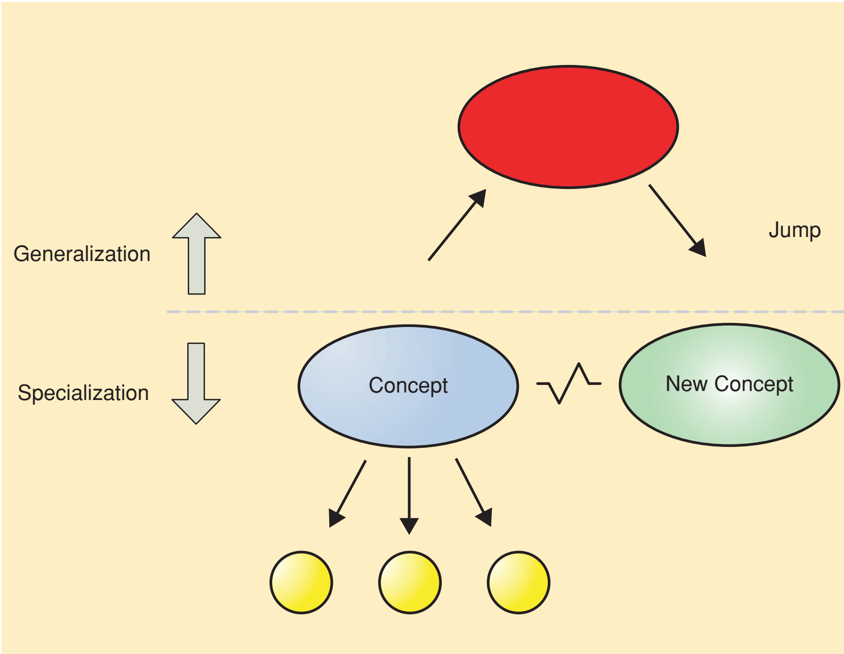
An important goal of this course was to communicate strategies used in engineering research to students from the arts. This was important for the students to understand connections among the different filters/operators used on sound/images. The goal was to make the students think in terms of the underlying generative model when dealing with content, beyond the immediate manifestation.

A typical generalization-specialization research strategy for improvement of a given concept is the identification of concepts that are more general than the current concept, and concepts that are specific instances of the current concept. For example, let us assume that alternate strategies to represent color images are developed, and the current strategy (concept) is that of an N-bin color histogram. Then specific examples of improving the representation may consist of changing the number of bins, the color space, or the bin widths. A concept generalization involves asking the question—of what is the current concept a specific example? A possible generalization is that a histogram is a specific example of a probabilistic representation of an image. Then, what are different probabilistic representations of an image? One such example is the Gaussian mixture model (as illustrated in Figure 3). The concept generalization idea is challenging for students even with a background in engineering. Hence, in this class we encouraged students to explore concept specialization systematically before developing a generalized understanding of the operator.

EVALUATION

A course that focuses on experiential understanding of signal processing concepts requires a different evaluation of the students. In homework the students were asked to evaluate media clips (images/sounds) and explain the types of operations that have been performed or to solve puzzles (e.g., dealing with probabilities). In the first case, the students were encouraged to use media programs such as Photoshop to determine the set of operations. The students were never asked to solve mathematical problems.

The final project was an important part of the evaluation. The students



[FIG3] **The generalization-specialization methodology allowed the students to form abstract connections between media operators that produce very different effects.**

could create any multimedia piece involving two different media types. The project had two important conditions attached: 1) the piece had to reflect their understanding of the key concepts taught in the class and 2) media elements that appeared at the same time had to be operated upon with filters/operators that had the same generalization. For example, let us assume that the students decided to blur a segment of video for two seconds. Then they needed to use an instance of the same generalization operator on the sound for two seconds. A possible generalization is that blurring is a specific instance of a low-pass filter for visuals. This would have required the students to use a low-pass filter on the sound as well.

The requirements mentioned earlier caused the media pieces to be structurally constrained, in the sense that multiple media streams that occur at the same time are constrained to refer to the same generalization. As a result, a successful student project would thereby reflect an understanding of the generalization-specialization methodology as well as an understanding of the operators and how to connect them via generalization across media types.

The student projects were all highly creative. The students were encouraged to work in pairs, given the complexity of the project, and they made use of audio-visual media or text and sound. For the students who had grasped the relationships across media streams at an abstract level, the final quality of the media result was high.

STUDENT FEEDBACK AND LIMITATIONS

The student feedback was highly encouraging. The students liked the new perspective brought by this course. One of the most gratifying comments was by a music Ph.D. student: "This has fundamentally altered the way that I think of music." There was some math in the class. We used [8] as a reference book, and we have not used a textbook in the class. Although we created original material to discuss most concepts, the students would have also preferred to be able to refer to a textbook in addition to the class notes. The sections that had the largest amount of experiential feedback (filters/sampling/convolution) were those that the students enjoyed the most.

CONCLUSIONS AND LESSONS LEARNED

In this article, we discussed our efforts to develop a signal processing course specifically designed for students with a background in the arts. The intended audience consisted of sophisticated media creators who lack a math background but are interested in developing a sophisticated signal processing understanding to aid their creativity. There were several key innovations: 1) the focus on developing a geometric perspective to teach signal processing, 2) the experiential introduction to signal processing concepts, and 3) the generalization-specialization process for developing a deeper understanding of media operators.

Overall, it was a difficult but rewarding exercise to teach signal processing concepts in a largely nonmathematical way. The biggest challenge was to develop a rich suite of examples that rewarded experiential interaction, replacing a mathematical explanation of the phenomena. We believe that the pedagogical approaches used in developing this course can also be useful at other teaching levels, including the high school level.

AUTHORS

Hari Sundaram received his Ph.D. from the Department of Electrical Engineering at Columbia University in 2002. He received his M.S. degree in electrical engineering from SUNY Stony Brook 1995 and a B.Tech in electrical engineering from Indian Institute of Technology, Delhi, in 1993. He is interested in developing computational models and systems for situated communication, with a focus on how semantics emerge though our engagement with the physical world. These interests have led to two complementary (but coupled) directions: designing intelligent multimedia environments that exist as part of our physical world and developing new algorithms and systems to understand the media artifacts resulting from human activity. Specific research activities include multisensory knowledge representation frameworks, algorithmic

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Todd Ingalls is a composer and computer artist who has been working with interactive performance and installations for the past several years. He is an active researcher with many of the ongoing research projects at the Arts Media and Engineering program, including immersive multimedia environments, and motion sensing and analysis. He is also a participating faculty member for the NSF CISE RI grant "An Interdisciplinary Research Environment for Motion Analysis" and an investigator on the "NEA Technology: Resources for Change" motion grant. His work has been performed internationally at SPIELART Theater Festival (Munich), VIA festival (Maubeuge), International Festival of Movement Arts (Bangalore), Cutting Edge Festival (Darmstadt), Zentrum für Kunst und Medientechnologie, and the Donaueschinger Musiktage.

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