

THE INFINITY PROJECT: DIGITAL SIGNAL PROCESSING AND DIGITAL MUSIC IN HIGH SCHOOL ENGINEERING EDUCATION

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ABSTRACT

The importance of mathematics and science education in modern technological society cannot be understated. This keynote paper outlines the structure and goals of The INFINITY Project, a joint effort between educators, administrators, and industry leaders to establish an engineering curriculum at the high school level. The curriculum motivates students to learn about the fundamental concepts and principles of mathematics, science, and engineering through the study of multimedia and information technology. Digital music and audio synthesis are used at the onset of this curriculum to teach students about signals, systems, and modeling. Several examples from this portion of the curriculum are described, including a real-time interactive waveform synthesizer, a real-time guitar synthesizer based on physical modeling, a real-time sinusoidal MIDI player, and an extremely low-cost loudspeaker that each student designs, builds, and tests.

1. INTRODUCTION

We live in a technology-driven society. The capabilities of computational devices have grown at an exponential rate over the past four decades, to the point where information processing by electronic devices is central to almost every aspect of modern society. These gains are largely due to the activities of engineers, mathematicians, and scientists who continue to explore new way to design, build, and test computational systems. According to Moore's Law, these gains are likely to continue at their current rates for the near future.

Who benefits most from such technological change? Clearly, those who study an engineering or technology discipline after high school will benefit throughout their lives from these advances because of their knowledgeable positions. It is becoming increasingly clear, however, that everyone in modern society requires a basic understanding of technology and how it is created. To reach the widest possible audience, this education must occur at the primary and/or secondary school levels. Current engineering and technology education at the pre-college levels is mainly focused on familiarity training with common technological devices, e.g. word processing with computers. What is needed is a broader focus on the design principles behind technology in a structured curriculum. Such a curriculum can also address another important issue facing our economy: While the number of jobs in the technology sector of the economy continues to grow, the number of college graduates in engineering and related technology disciplines continues to

fall. A well-designed, exciting, and relevant engineering curriculum at the pre-college level is likely to increase the numbers of students who enroll in college engineering and technology programs.

This paper outlines the structure and goals of The INFINITY Project, a joint effort between university educators, high school teachers and administrators, and industrial leaders to establish a viable engineering curriculum that is taught within the regular high school day. The curriculum teaches students about the design of technology-driven systems and motivates them to learn fundamental concepts of mathematics, science, and engineering. Digital music and audio synthesis are used at the onset of this curriculum to teach students about signals, systems, and modeling. This paper delves into the details of this portion of the curriculum and describes the concepts and ideas illustrated in these lessons. Several educational examples of this portion of the curriculum are described, including

- a real-time interactive waveform synthesizer,
- a real-time guitar synthesizer based on physical modeling,
- a real-time sinusoidal MIDI player, and
- an extremely low-cost loudspeaker that each student designs, builds, and tests.

2. DESCRIPTION OF THE INFINITY PROJECT

The INFINITY Project consists of five key elements:

- 1) A textbook with example problems that contains the core content of the course;
- 2) A set of laboratory exercises that are integrated with the textbook content and that are performed by the students in a computer laboratory setting;
- 3) A low-cost software/hardware laboratory kit that each student uses to perform their experiments and gain immediate feedback;
- 4) Summer training institutes for high school mathematics and science teachers to learn how to teach the curriculum; and
- 5) A web-based portal that allows teachers to interact with the curriculum designers during the school year and address any day-to-day and week-to-week concerns about their particular course.

During the 2000-2001 pilot school year, fourteen schools from the Dallas, Houston, and San Antonio, TX, areas taught the INFINITY Project curriculum to approximately 500 total students. In the 2001-2002 school year, 40 schools from 10 different states are teaching a re-designed version of the

curriculum to approximately 1500 total students. In addition, the Texas Education Association has given statewide approval to the curriculum, such that any Texas high school can offer one mathematics credit or one science credit to any student taking the course. We intend to grow this program to approximately 1000 schools and 50000 students across the U.S. by 2005-2006. The growth in the program does not appear to be limited by interest; rather, it is driven mainly by the growth of the number of qualified summer training personnel, the majority of whom shall be drawn from the ranks of high school teachers that have taught the course.

A brief description of each component is now provided.

2.1. The Textbook

The textbook for the course, entitled *Multimedia and Information Engineering* [1], focuses on the design and implementation of information-based technology. While any one of a number of core topics could be chosen for a high school engineering course, we have focused on multimedia and information technology as the core subject areas for three main reasons:

- 1) Everyone is likely to benefit from having general knowledge of these areas in later life, no matter what their profession might be.
- 2) Engineering design principles for these devices can be taught without the need for senior- or college-level calculus.
- 3) Most students are familiar with and enjoy one or more aspects of these areas, whether they listen to music, go to the movie theater, or communicate using cellular telephones or the Internet.

The textbook has been written with a “top-down” focus on particular problems in the following areas:

- Technology projections
- Digital music, audio synthesis, and sound effects
- Digital image analysis and manipulation
- Communication systems and networks
- Information storage, encryption, and error correction
- Hardware implementations of systems

Each chapter contains problems to be solved by hand and calculator as well as “just-in-time” in-text pointers to relevant laboratory exercises, to be described shortly. The textbook has also been designed for flexibility: the first 8 chapters represent core material that covers essential topics, whereas the remaining 10 chapters provide enrichment material to the core chapters’ content. The mathematical prerequisites for the course are Algebra II, and no calculus is used or needed.

This 700-page textbook is the result of a two-year design process. In January 2000, a meeting was held between the textbook authors, twenty high school teachers from across Texas, and members of an advisory board consisting of university faculty, industrial partners, high school administrators, and educational advisors. At that meeting, detailed parameters of the curriculum were specified, including the level of mathematics and science to be taught, the technology for and scope of the laboratory component of the curriculum, and the topics to be covered. During a second follow-up meeting in January 2001, the initial impact of the curriculum was assessed, and a complete re-design of the text was fashioned to better meet all students’ needs.

2.2. The Laboratory Exercises

Integrated within the course textbook are laboratory exercises that illustrate and apply important engineering design principles. These laboratories are in the form of (1) an HTML webpage that describes the task(s) to be completed, and (2) a software worksheet that contains a functional block diagram of the system to be designed and tested or the blocks needed to build such a design from scratch.

The software environment used for the worksheet is Visual Applications Builder (VAB) by Hyperception, Inc. VAB is a scaled-down version of Hyperception’s core DSP design software that high-technology companies use to prototype real-time signal processing systems. It is a flexible design environment involving only icons as software modules, and students need not learn programming to run existing worksheets nor to build new ones. The programming methodology involves simple rules regarding signal flow graphs that the students quickly master. All of these laboratory exercises are available at no cost through The INFINITY Project web portal for participating high schools and run on the INFINITY Technology Kit, to be described next.

Examples of laboratory worksheets that the students design and build, ignoring music-related ones, include:

- a visual object tracker that tracks moving objects in a video stream;
- a coin counter that counts the number of a certain type of coin in a fixed or moving image;
- a color image/video display with adjustable quantizer resolution; and
- an audio transmitter and receiver that communicates text messages across the room in real-time.

2.3. In-Class Laboratory Technology



Figure 1. The INFINITY Technology Kit.

The INFINITY Technology Kit is a low-cost hardware and software kit that students use to design, build, and test their real-time signal processing designs. The Kit includes:

- a Texas Instruments TMS320C31 Evaluation Module (EVM) with power supply,
- Hyperception’s VAB software,
- a microphone with battery-powered preamplifier,
- a pair of powered loudspeakers,

- red/blue glasses for stereoscopic image processing experiments, and
- all necessary cables and adapters.

The Kit connects to a Windows-based PC through its parallel port and allows for one-button-push programming and execution of VAB worksheets on the TMS320C31 EVM. The EVM is currently only utilized for real-time audio experiments; video experiments are PC-based and employ files and video camera streams as inputs. Real-time data transfers from the EVM to and from the PC are used within the VAB worksheets to enable students to interact with the DSP-based programs while they are running and to analyze the system's inputs and outputs.

2.4. Summer Training Institutes

Currently, there are very few high school teachers in the U.S. who are trained as engineers, and no state has established high school teacher certification procedures in engineering. To meet the teaching needs of the INFINITY curriculum, we have developed a 40-hour, five-day summer training institute. This institute provides each high school teacher with a brief but intense exposure to the curriculum, training on the use of VAB and laboratory worksheets, and extended time for developing and exploring individual VAB designs. No attempt is made to "teach the entire book" to the teachers; rather, emphasis is placed on the engineering design process and the way engineering differs from the core mathematics or scientific discipline of each teacher. For the past two summers, all institutes—six in total—were held on the campus of Southern Methodist University in Dallas, TX. One institute was actually run by two high school teachers, both of whom had taught the course in the pilot year, with minimal expert assistance. In the summer of 2002, these institutes will be held in various parts of the U.S. at regional host universities and institutions. Partnerships with several regional universities and institutes have been forged to provide local assistance with training.



Figure 2. *Summer Training Institutes.*

2.5. Web-Based Information Portal

All teachers dynamically adjust their teaching schedule and methods to meet the needs of their students. To make sure our high school teachers have the resources that they need to be

successful, we have developed a web portal for information delivery and discussion (www.infinity-project.org). This portal houses:

- discussion groups on curricula and technology issues;
- VAB laboratories and worksheets;
- sample test questions with solutions; and
- links to relevant web sites

along with news and general information about The INFINITY Project. While we currently provide 24-hour turn-around responses to urgent teacher questions, many of our teachers offer answers to other teachers' questions when they can.

3. DIGITAL MUSIC AND AUDIO SYNTHESIS

In the initial design of the INFINITY Project curriculum, we as authors recognized the importance of music to motivate the understanding of fundamental concepts in one-dimensional signals and their manipulation. Almost everybody listens to music. Music also provides direct links to important concepts in mathematics and science. Some of these concepts include period, frequency, amplitude, spectra, wavelength, time delay, the decibel scale, sinusoidal signals, and exponential decay. Our goal was to uncover these concepts through a top-down design problem involving a relevant task to the students. The result of this effort became Chapters 2 and 3 of the course text, which represent approximately 25% of the core material.

The task that introduces Chapter 2 and is continued with slight modification in Chapter 3 is easily appreciated:

"Suppose a group of your friends have gotten a band together. Everyone is bringing a different musical instrument to play. You want to join in on the band, but you're not sure which instrument you want to play. In fact, different songs are going to require different instruments, so you want to be able to play a number of different ones. The only problem is, you don't have any of these instruments, and you probably don't know how to play all of them. How can digital technology still make it possible for you to be in the band's spotlight?"

Rather than describe the procedure for addressing this design problem, which can be readily surmised from the course text, we will illustrate how certain important mathematical and scientific concepts are interwoven with experiments that show their importance, validate a student's understanding of them, and lead to engineering designs that make useful sound. Each description will take the student's perspective, although advanced terminology will be used where appropriate.

3.1. Waveform Synthesis

One important aspect of the engineering design process is the collection of data relevant to the problem at hand. It is a relatively simple matter to plot audio waveforms as measured by the microphone of the Technology Kit and study their structure. When one plots the sound waveforms of several different musical instruments at both coarse (several seconds) and fine (several milliseconds) scales, one discovers that they all have to a first approximation two structures to them. The coarse

amplitude structure, termed the *envelope signal* $e(t)$, describes the overall loudness of the sound, whereas the fine structure of the sound $p(t)$ repeats over and over. This *periodic signal* has a repeating interval T , called the *period* of the sound, that is connected with how “high” or “low” we perceive the pitch of the sound to be. Clearly, if one can represent both $e(t)$ and $p(t)$ to high enough accuracy, then one can create an approximate version of the overall sound using the rule

$$s(t) = e(t) \times p(t) \quad (1)$$

Multiplying the two signals makes sense because $e(t)$ does not change much over any one repeating interval, thereby scaling the amplitude of the sound as desired.

The VAB worksheet that implements this simple waveform synthesis procedure is shown in Figure 3. Called SketchWave, it has two “sketchpads” where the unique portions of $p(t)$ and $e(t)$ can be drawn using the mouse. Two sliders can be used to adjust the time lengths of each sketchpad. Because all interfaces in the experiment interact with the DSP EVM in real time, one can fine tune the sound output *while the worksheet is running*, giving a high level of interactivity. Finally, clicking on the “Freq” button on the multipurpose display on the upper right portion of the worksheet, one can see a new representation of the sound waveform, called the *spectrum*, and through experiment learn the relationship between the period T and the *fundamental frequency* f_0 of the sound.

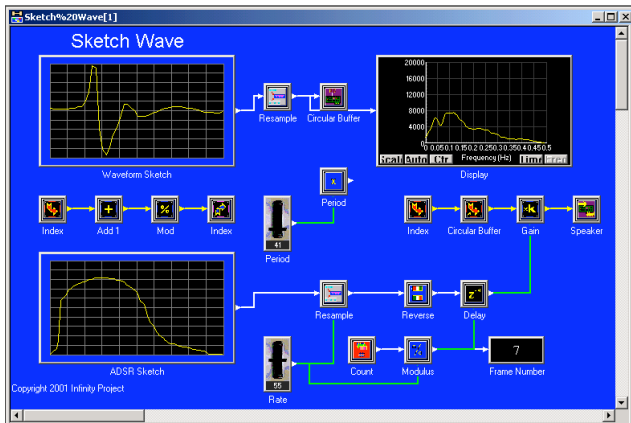


Figure 3. Waveform Synthesis Using SketchWave VAB.

3.2. Physical Modeling

Another important engineering tool is *modeling*. Modeling allows one to capture all of the relevant behavior of a system by describing the function of each of its parts as well as how these parts are connected together. Through the power of computation, we can even use models in place of the real-world systems on which they are based, particularly in the case of musical instruments. To understand how musical instruments make sound, we need to know

1. what a *traveling wave* is,
2. what happens when a traveling wave hits a hard surface, resulting in a *reflection*, and
3. how *losses* in the system cause the amplitudes of these waves to decay after every pass unless energy is continually added.

We can use visual analogies to illustrate certain concepts (e.g. Why does left become right when you look in a mirror? Do you expect your reflection to be brighter or darker than yourself?), or we can perform simple experiments with loose rope to see what happens in different situations. For other concepts, we can provide equations that describe the relevant behavior (e.g. sinusoidal traveling waves) without starting from first principles. Then, connecting these individual concepts together, we obtain a mathematical model that represents the physical behavior we are trying to emulate.

Figure 4 shows the well-known digital waveguide model of a guitar string with frequency-independent losses [2]. Notice that its parts—the buffers containing the string displacements and the lossless and lossy inverter on each end—can be justified from the previous discussion. Figure 5 shows the VAB worksheet that implements the guitar string model. Displacement can be drawn using a sketchpad, whereas string length and pickup position can be chosen via sliders. This VAB invites a great number of exploratory exercises. For example, how would you choose the loss parameter a to make a banjo sound? What if you make a slightly greater than one? What sound do you expect to hear if you draw a “notch” string displacement instead of a triangular string displacement?

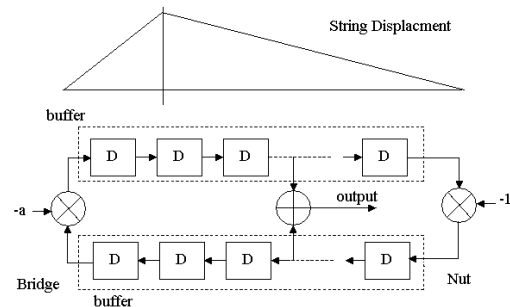


Figure 4. Block diagram of a guitar string model.

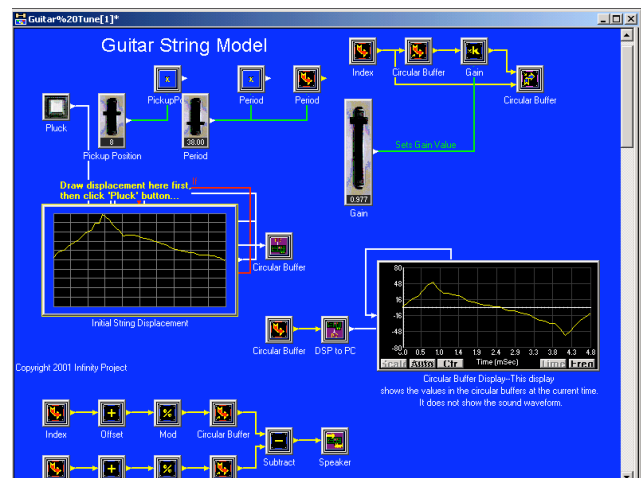


Figure 5. Guitar String Model VAB.

3.3. Sinusoids as Music

Most everyone has heard the din of pre-programmed songs from electronic keyboards in an electronic appliance store. Most everyone has not given much thought as to how these devices

work. How does one store musical performances for playback at a later time?

Musical instruments can “carry a tune” because their waveforms are nearly-periodic. Melodies, however, are made up of waveforms with varying fundamental frequency. While a signal with fixed frequency content can be accurately displayed using the spectrum, we need a slightly different display for understanding music—one that adds a time dimension to the spectral plots. We call such 2-D images *spectrograms*. Sheet music is a type of spectrogram, and so are MIDI files, because they store time-varying frequency information in numeric form. To play music, all we need to do is to feed this frequency information into devices that change their fundamental frequency as the melody changes. Sinusoidal signals are examples of simple periodic signals. So, we can create a sinusoidal synthesizer that plays MIDI files by simply connecting the frequency information from the MIDI information stream to the frequency parameters of the sinusoids and adding the resulting waveforms together.

Figure 6 shows the VAB worksheet for a sinusoidal MIDI player. The yellowish block on the left-hand-side is not a piano keyboard; rather, it simply receives a MIDI data stream being played by a MIDI player within the Windows environment and extracts its real-time frequency information. The signal flow through this worksheet is easy to understand, and in fact this VAB is one of the first in the course that the students build themselves.

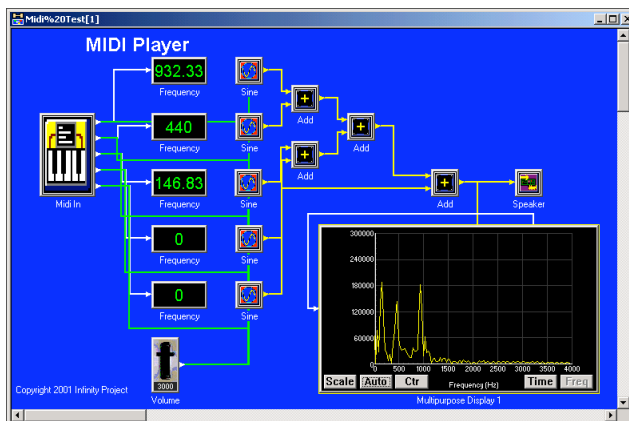


Figure 6. *Sinusoidal MIDI Player VAB.*

3.4. A Low-Cost Loudspeaker

Loudspeakers are simple transducers, consisting of a magnet, a coil, a cone, an enclosure, and some adhesive. They function according to Oersted’s Law, which governs the operation of all electromechanical systems. The materials needed to build a loudspeaker are not exotic; hence, they can be built at extremely low cost. Figure 7 shows one such design, names the Gosney speaker after its inventor, a professor of electrical engineering at SMU. This speaker consists of a button magnet, a coil of insulated copper wire, a paper cone, a Styrofoam salad bowl, and some glue. The total materials cost of this design is about US\$0.35 or somewhat less than a candy bar.

High school teachers are encouraged to use sound pressure level measurements from a simple handheld sound meter for a given volume setting and signal content to grade each student’s

design. Depending on the amplification level, volumes of over 100dBA SPL at the cone’s center are not unheard of, although the low-frequency performance of the overall design is lacking. Even so, it is pretty amazing to hear recognizable sound from a speaker costing about a third of a dollar! In addition, the speakers also function quite well as microphones.



Figure 7. *The Gosney Speaker.*

4. CONCLUSIONS

The INFINITY Project offers high school students an opportunity to learn about engineering design principles in the context of information technology. Digital music is an integral part of the curriculum, teaching important concepts about signals, systems, and modeling. Laboratory experiments using real-time signal processing hardware and software help to illustrate important subject matter in practical settings.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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