Sonification of Chemical Engineering Data

An Interactive Qualifying Project completed in partial fulfillment of the Bachelor

of Science degree at Worcester Polytechnic Institute, Worcester, MA

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Abstract

Chemical engineering concepts are generally taught using visual learning methods: engineering components are sketched, data is plotted, and equations are solved graphically. This approach to problem-solving has proven successful for visual learners, who comprise the majority of students pursuing STEM fields; however, this method of problem-solving may hinder students that prefer alternate learning methods. The purpose of this study was to determine whether auditory learners benefit from auditory-based feedback. Simultaneously, we determined whether visual learners benefit from visual-based feedback. We paired visual learning with auditory learning to improve learning outcomes in challenging chemical engineering concepts, particularly multiple steady states (MSS) and proportional-integral-derivative (PID) control. MSS and PID control were presented through auditory means by sonifying temperature and heat output data streams. The data streams were also presented visually by providing graphical representations. The software Simulink generated the data streams and presented them graphically, the software Python converted the data streams to a text file, and the software Max pitch-mapped the data streams to sound. With the WPI course CHE 3301 as a test bed, twenty-three undergraduate chemical engineering students completed a preliminary survey to determine their preferred modes of learning, completed an assignment that presented MSS and PID control through auditory and visual means, and then completed a post-survey to assess whether they learned the material from the auditory component of the assignment, the visual component of the assignment, or a combination of the two components. The data suggested that auditory learners benefited from auditory-based instruction, though there was substantial scatter in the data. There was no correlation between aptitude for visual learning and visual-based instruction.

<u>Acknowledgements</u>

Authorship

This report was written by Krishna Mahalingam, Andrew Ollerhead, and Jonathan Vardner. All of these individuals are responsible for the contents of each section of this report.

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Executive Summary

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Abstract

Chemical engineering concepts are generally taught using visual learning methods: engineering components are sketched, data is plotted, and equations are solved graphically. This approach to problem-solving has proven successful for visual learners, who comprise the majority of students pursuing STEM fields; however, this method of problem-solving may hinder students that prefer alternate learning methods. The purpose of this study was to determine whether auditory learners benefit from auditory-based feedback. Simultaneously, we determined whether visual learners benefit from visual-based feedback. We paired visual learning with auditory learning to improve learning outcomes in challenging chemical engineering concepts, particularly multiple steady states (MSS) and proportional-integral-derivative (PID) control. MSS and PID control were presented through auditory means by sonifying temperature and heat output data streams. The data streams were also presented visually by providing graphical representations. The software Simulink generated the data streams and presented them graphically, the software Python converted the data streams to a text file, and the software Max pitch-mapped the data streams to sound. With the WPI course CHE 3301 as a test bed, twenty-three undergraduate chemical engineering students completed a preliminary survey to determine their preferred modes of learning, completed an assignment that presented MSS and PID control through auditory and visual means, and then completed a post-survey to assess whether they learned the material from the auditory component of the assignment, the visual component of the assignment, or a combination of the two components. The data suggested that auditory learners benefited from auditory-based instruction, though there was substantial scatter in the data. There was no correlation between aptitude for visual learning and visual-based instruction.

Introduction

Auditory learning is a preference of learning through listening to spoken lessons and instructions, dialogue, and to a lesser extent mnemonics, rhymes and rhythms. People may be classified as auditory learners if they find the aforementioned learning methods more effective than visual or tactile methods. Though some studies have refuted the belief that people are predisposed to learn more effectively via one sensory stimulus than any other, people commonly distinguish themselves as visual, auditory, or kinesthetic learners based on the method through which they prefer to be taught. The absence of auditory learning methods in college lectures, including in STEM fields, has not gone unnoticed. The typical auditory component of a STEM lecture only extends as far as textbook reviews, explanations of graphs and tables, and clarifications regarding written equations. In other words, auditory instruction is sparingly used, and only as a tool to aid visual instruction.

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This project is devoted to creating an application that will interpret data pertaining to multiple steady-state reactions and algorithmically rearrange this data into music which can be implemented as a tool to aid visually-presented data, thus providing auditory learners with more resources to understand the topic. Drawing inspiration from existing auditory learning programs, this application composes music that is pleasing to listeners and comprises a lead musical component as well as backing music that reinforce understanding when played in conjunction with a visual component. Both of these musical elements represent important values and conditions that aid students in understanding chemical engineering concepts.

Methodology

We designed an assignment that incorporated a combination of auditory and visual learning. The assignment was designed to test whether the sonification data streams can help auditory learners understand PID control and MSS. We presented this assignment to 23 students in the course: *ChE 3301 Intoduction to Biological Engineering*. The assignment consisted of four sections: a preliminary survey, background reading, a chemical engineering problem, and a post survey.

We included the preliminary survey to obtain information on each student's preferered learning modes. We chose to use the VARK (visual, auditory, read/write, kinesthetic learning) questionnaire as the preliminary survey. This questionnaire estimates its ability to characterize visual learners with 85% accuracy and auditory learners with 82% accuracy. Because the project aims to assess the potential benefits of auditory learning, it was important to determine the learning preferences of each student.

The background reading consisted of preliminary information on PID Control in MSS. These topics were not previously covered in the course. Therefore, we needed to verify that each student had the proper information needed to complete the assignment.

To design the chemical engineering problem, we needed to model a continuously stirred tank reactor (CSTR) in Simulink, an extension of the software MATLAB. The CSTR was considered to consist of three regions: the heat gained from a chemical reaction, the heat removed by the cooling water, and the PID control system. The objective for the student was to tune the control parameters of the PID control system to converge the CSTR temperature from the stable upper steady state condition to the unstable middle steady state condition. The students were guided through the *Riggs Tuning Method* to find appropriate control parameters. Simulink produced graphical representations of the CSTR temperature and the heat output from each control parameter in the PID control system. Simulink also produced the data set in tabular form, which was subsequently put through formatting steps. The tabular data set was then accessed through a custom-made application in Max, a programming language dedicated to music and multimedia software. Our Max application followed a series of customized algorithms designed to represent the data musically, by mapping values to pitch through MIDI and changing the volume of background instrumental audio tracks.

After each student completed the chemical engineering problem, they each took a post-survey. The post-survey assessed whether each student learned the material from the visual representation of data, the auditory representation of data, or a combination of the two representations of data via a series of Likert-scale questions. Each student also recorded their

results for the control parameters in Simulink so that we could verify that each student successfully completed the assignment.

Results

The assignment was designed to test whether the sonified data streams helped auditory learners understand PID control and MSS. Using the preliminary survey and post survey data from 23 students, we plotted the helpfulness of the auditory component of the assignment against the students' capacity to learn by auditory means, as determined by the VARK preliminary survey. The results are shown below in Figure 1.
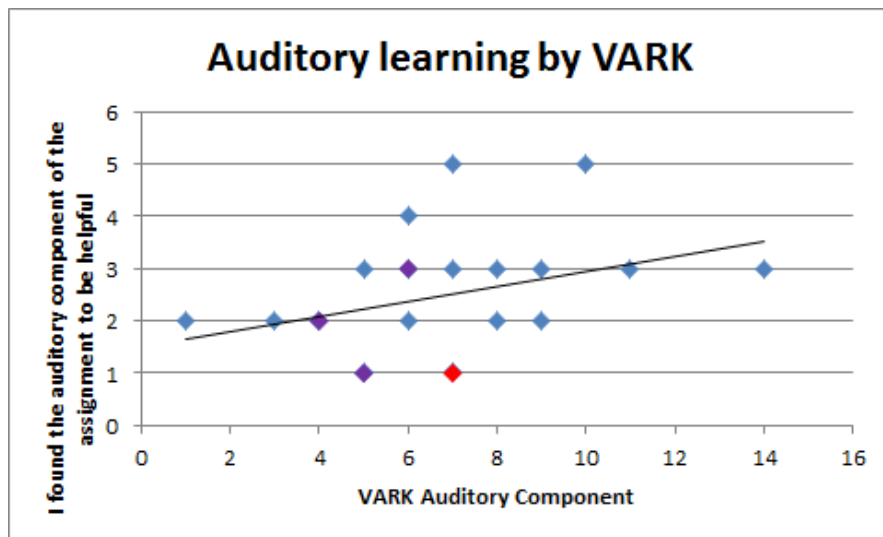
Figure 1: Plot showing the trend that the auditory component of the assignment helped auditory learners learn the material. The blue points represent one student, the purple points represent 2 students with the same scores, and the red point represents 3 students with the same scores.

The above figure depicts the general trend that the sonification of the data streams helped students with a preference to auditory learning. This data supports the claim that sonification of data has potential to help auditory learners understand engineering principles. The Likert-Scale produced ordinal. This data type consists of a ranked set of numerical scores without exact numerical quantities. The mean and standard deviation are generally considered to be statistically invalid for this data type. Rather, the median and mode are more appropriate for statistical analysis. The median and mode values for the VARK auditory score were each 7. The median and mode for the usefulness of the auditory component of the assignment were 2 and 3 respectively.

We statistically analyzed whether the scatter in the data affected our ability to make significant claims about the data through the use of Chi-squared analysis. This analysis determines the likelihood that the correlation between data sets is due the random sampling distribution. We analyzed whether there was a reproducible correlation between the VARK auditory scores and the usefulness of the auditory component of the assignment. Using the Chi-

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squared test, we determined that there was a 42% chance that the correlation was due to the random distribution of students that took the assignment. This is far above the 5% threshold that is commonly held to make significant claims about data. There was error in the Chi-squared test due to our low population size; the Chi-squared test is an approximation that loses its validity when the population size is small. We recommend applying Fisher's exact test on the data set to determine the correlation without mathematical approximations. This analysis cannot be done on our set of data without the aid of software packages.

Next, we plotted an analogous graph portraying the helpfulness of the visual component of the assignment against their capacity to learn by visual means. The results are shown below in Figure 2.
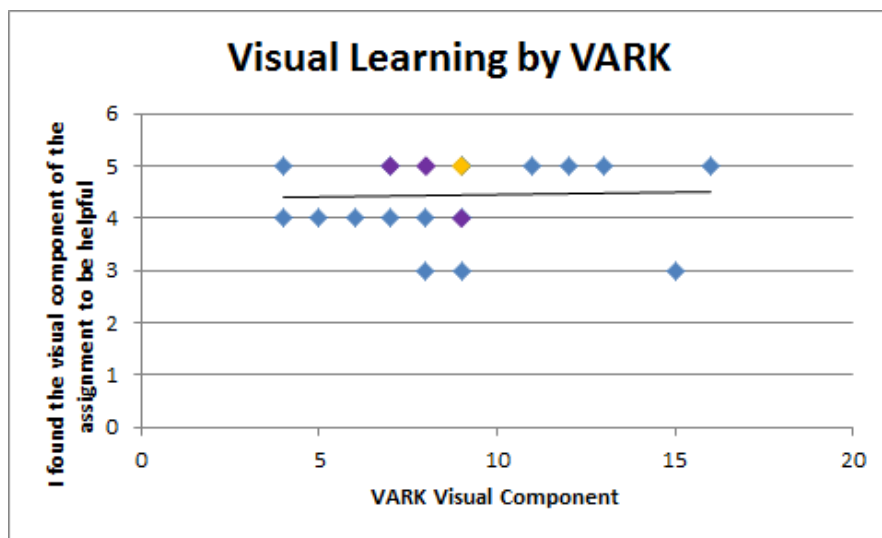
Figure 2: Plot showing the trend that the visual component of the assignment helped students consistently regardless of visual learning capacity. The orange-yellow point represents 4 students with the same scores.

Figure 2 reveals no correlation between the utility of visual components and the propensity of subjects to be visual learners. From the Chi-squared test, we determined that any correlation would have a 73% chance of occurring due to the random distribution of students. The data suggested that all students learned from the visual component consistently regardless of their capacity for visual learning. We expected there to be a positive trend between these variables. The median and mode values for the VARK visual score were each 9. The median and mode values for the usefulness of the visual component of the assignment were each 5. We determined that more students tended to be visual learners than auditory learners from the VARK survey. Likewise, students generally deemed the visual component of the assignment to be more useful than the auditory component of the assignment.

We decided that there could have been factors influencing the data. These factors consisted of: the disposition of each student to mark answers high or low, the unclearness of the instructions, the validity of the VARK survey, whether the students were provided enough background information to understand the assignment, and whether each student completed the full assignment. We analyzed these potential sources of error using the data of other survey

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questions. We determined that the instructions were clear, the students were provided enough background material, and the vast majority of the students completed the assignment appropriately. We were unable to validate the VARK survey, though the survey is estimated to be accurate by its creators. The primary source of error was likely the disposition of each student to answer survey questions with high or low scores.

Conclusion

We determined that the auditory component of our software helped several students understand the material; however we were unable to statistically determine that there was a correlation between a preference for auditory learning and the usefulness of the auditory component of the assignment. We found that the majority of students preferred visual learning to auditory learning based on their VARK preliminary scores and their stated personal preferences in the post survey. Nevertheless the majority of students benefitted from auditory learning methods to some extent regardless of their dominant learning style. Auditory learning has an important role in the classroom, though educators should consider the extent that auditory learning should be used at the undergraduate level.

Recommendations

Auditory learning could potentially lead to improved learning outcomes in different age groups. It is very possible that younger students would prefer auditory learning more than undergraduate students. Younger students may have turned away from engineering because they did not enjoy its visual learning style. Presenting engineering concepts to younger students with auditory learning may attract more auditory learners to the engineering discipline. We recommend a study be completed to determine whether auditory learning can improve learning outcomes in students in the middle-school or high-school level.

1 - Introduction

The goal of Worcester Polytechnic Institute's chemical engineering curriculum (or that of nearly any school's curriculum) is to aid students in understanding a well-defined set of principles, theories and calculations, as well as their applications in engineering industries. However, there are those who would like to pursue a degree in chemical engineering, but don't learn effectively through common teaching strategies which prioritize printed tables, graphs and figures to reinforce principles and convey tools and methods, instead preferring to learn using strategies that target different senses, conveying information through sound or reinforcing concepts through physical movements. Though it may be possible to accommodate these students' learning preferences in an alternative classroom setting, large class sizes and short academic quarters at WPI (compared to typical engineering programs) require instructors to adhere strictly to the curriculum, and drastic modifications to the chemical engineering curriculum rarely come about without a long trial process and universal support from instructors and faculty alike.

Based on the curriculum's almost exclusive reliance upon visual resources as learning aids, one might infer that chemical engineering courses offered at WPI give visual learners a clear advantage over auditory or kinesthetic learners. Whether or not visual learners, on average, score higher on examinations than classmates with different learning preferences has not been conclusively proven or disproven, but regardless, it would be wrong to assume that all visual learners are exempt from challenges that may hinder their understanding of chemical engineering concepts. For example, chemical engineering students at WPI often struggle when learning the subject of reactor design, simply because this subject introduces a wide array of different reactor models and unique equations which are rarely encountered in prerequisite courses. Due to the

complexity of multiple steady state (MSS) reactions in particular, and the methods used to model their behavior, many chemical engineering students, regardless of learning preference, find that they are not intuitively equipped with the tools necessary to solve problems of this type. MSS reactions are encountered commonly in industry, but require an extensive length of time and breadth of background knowledge to obtain a comprehensive understanding of the topic. According to professors in the Chemical Engineering Department, WPI has been met with difficulty when integrating the subject of MSS reactions into the curriculum, resulting in the subject of MSS reactions being classified as an "advanced topic" that has not been covered extensively in any course for many years.

The curriculum does not address MSS as a core subject, instead prioritizing concepts that are universally relevant within the broader scope of reaction engineering. These concepts, however, are rarely applicable to more than one type of reaction, and the curriculum's treatment of these concepts as foundational elements is a reflection of the shear breadth of topics addressed in reactor design. An instructor seeking to teach MSS comprehensively alongside the fundamental concepts of reactor design must realize that the length of time needed to introduce all necessary course material in a typical lecture format (that relies upon visual means) does not coincide with the short, fast-paced terms of WPI classes. It is possible that by providing graphs or other visual sources of data together with a complementing audio component, students are encouraged to think about the data differently than if only a visual source was present. The accompaniment of data-representative music or other sounds could passively provide students with several individual sources of information that may help them understand the circumstances of problems and concepts in less time than would be required to present everything through written summaries, graphs or figures.

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2 - Background

2.1 - Auditory Learning

The study of learning types, their distinctions and their effects on human behavior and overall mentality became a subject of interest among psychologists and sociologists in the 1970s. These researchers hoped to prove that not all minds are inherently alike and in doing so, promote different methods of teaching and communication that would appeal to a more diverse range of people who may differ in learning preference (Grinder & Bandler, 1976). Though some studies have refuted the belief that people are predisposed to learn more effectively via one sensory stimulus than any other, people commonly distinguish themselves as visual, auditory, or kinesthetic learners based on the method through which they prefer to be taught.

2.1.1 - Research and Diagnostic History

The first concept to gain widespread notoriety was neuro-linguistic programming (NLP), which suggested that a person's predisposed approach to communication (and by extension, their primary modality of learning) has a profound effect on their personal development. This concept claims that if a person approaches a new subject that is represented through only one modality to which they are not prone (i.e. if an auditory learner is only provided with the visual means to learn – mismatching representational systems) then they are significantly more likely to be diagnosed with a learning disorder, experience anxiety and depression, or suffer from a lack of confidence in their learning abilities (Dowlen, 1996). Observing historical context, it is now understood that the NLP approach would not have gained such notoriety had it not been introduced against the backdrop of the emerging self-esteem movement of the 1960s and 1970s. The proposed links to an increase in mental disorders (extending to problems such as allergies

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and myopia) were unfounded, causing NLP to be discredited and labeled a pseudoscience (Bradley & Biedermann, 1985). However, the concept of different representational systems and their characteristics spurred a larger interest in learning modalities, which psychologists sought to further research and define. One highly regarded model to expand upon NLP representational systems is Neil Fleming's VARK model, which has been commended as having rigidly defined learning styles and recognizing common traits among visual learners, auditory learners, reading-writing preference learners, and kinesthetic (tactile) learners (Fleming, 2014).

Though several different models have been designed, the intended application of most seems to revolve around the "meshing hypothesis," which suggests that instruction is most effective when provided in the format that matches the learner's preference. For example, the hypothesis suggests the most effective instruction for a visual learner would be a visual representation of the information being provided (Pashler, McDaniel, Rohrer & Bjork, 2008). However, in the 1980s, Grinder and Bandler rejected their previously proposed meshing hypothesis, stating that people are not restricted to one modality of learning or thinking, but rather use all senses when receiving and interpreting instruction, concluding that the most effective instruction for most people is given in a way that appeals to multiple senses. Therefore, auditory learning methods should be mixed with visual and reading-writing methods to promote the most profound level of understanding. One or more of these methods are often left out of an instructor's curriculum either for brevity or to alleviate some difficulties of instructing large groups at once (Bradley & Biedermann, 1985).

2.1.2 - Auditory Learning and Education

Auditory learning is a preference of learning through listening to spoken lessons and instructions, dialogue, and to a lesser extent mnemonics, rhymes and rhythms (or otherwise musical methods). People may be classified as auditory learners if they find the aforementioned learning methods more effective than visual or tactile methods (Ross, 2001). While college students who are recognized as auditory learners typically benefit substantially from actively listening in lectures and discussing lecture material with professors, teaching assistants and peers, lessons are not often formulated in a way that optimizes auditory learning.

Most lectures include an auditory component, in the form of an instructor explaining a particular subject or displaying a narrated video, but it is becoming increasingly less common for college classes to integrate class discussions with lectures, particularly in the fields of science, technology, engineering and math (STEM). Barring in-class discussions, STEM courses rarely implement novel tools for auditory learners such as mnemonic devices or sonically represented data (such as audio files or interactive software), instead favoring graphs, tables and calculations. The vast majority of concepts in the STEM field, both in the classroom and in industry, are taught using methods that favor visual and reading/writing learning. This led educational learning researchers David Kolb and Ron Fry to hypothesize that auditory learners must adapt to less-intuitive learning styles to succeed in STEM fields, and that many auditory learners avoid STEM fields altogether due to their difficulty in learning the subject matter through the available models (Kolb, 1984).

2.1.3 - Noteworthy Approaches

The absence of auditory learning methods in college lectures, including in STEM fields, has not gone unnoticed. The typical auditory component of a STEM lecture only extends as far

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as textbook reviews, explanations of graphs and tables, and clarifications regarding written equations. In other words, auditory instruction is sparingly used, and only as a tool to aid visual instruction. Over the past twenty years, however, advancements in technology have facilitated the development of software that aims to teach scientific concepts primarily through the use of sound in the form of a distinct tone or a representative song or audio sample. Interestingly, though a handful of researchers and developers have created software that sonically present data pertaining to a wide array of scientific topics, almost no two examples of aurally represented data are identical or seem to follow the same convention. Some already-existing projects serve to provide audio as the sole representation of data. One piece of software, developed in Universidade Nova de Lisboa for the blind and visually impaired, translates visually-available infrared spectroscopy (IR) into MIDI by allowing increases in pitch to represent increased infrared light absorbance while allowing the passing of time within the sample to represent increasing spectral frequency. Students using the software must be trained to recognize certain sound clips that represent the presence of functional groups, not unlike the way that non-visually impaired students must learn to recognize spikes in the graph that represent the same. This gives blind and visually impaired students a useful tool to analyze IR spectra and extract all of the data that the visual equivalent presents (Pereira, Ponte-e-Sousa, Fartaria, Bonifacio, Mata, Aires-de-Sousa, & Lobo, 2013).

Another standalone application called Protein Music (PM) has served as a continuous reference point in the field of auditory learning software, having been cited in hundreds of published studies since its own publication in 1996. The purpose of this application was to translate the inherently one-dimensional sequence of nucleotides, which code for DNA, into a musical composition using an algorithm that assigns one note to each of the four nucleotides

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found in DNA and plays these notes in succession to the signature of three beats per measure. The simple but symbolic melody is accompanied by an equally representative bass line that is designed algorithmically to describe chemical properties of the sequence (such as polarity or charge), changing throughout the piece to indicate different properties as they appear in the nucleotide chain. The software developers make no mention of the blind or visually impaired, but nevertheless states that sonification "possesses the [unique] property that when different notes are played together they can still be individually heard," asserting that this property can be "very useful when studying multivariate data" (King & Angus, 1996). Paul Vickers of Northumbria University asserted that patterns (such as those commonly expressed in programming) may contain errors or change suddenly, and that the recognition of this discontinuity is "more intuitively obvious to our ears than our eyes" (Vickers, 2004). Vickers also proposed that analysis of these patterns is more efficient when the data is presented sonically, asserting that, unlike visual data, "sound can be processed by the brain passively… we can be aware of sounds without needing to listen to them," providing analysts with a method less tedious than combing through a plethora of data points and actively looking for a point in which the pattern ends.

In many cases the strictly aural presentation of data is sufficient for analysis or for use as a study tool, but many software developers feel that visual accompaniment is also necessary to "provide a context or framework for the audio sound track" (Vickers, 2004). Consistent with Grinder and Bandler's ultimate findings, many teaching applications that provide an auditory component use it in conjunction with visual representations of the same information (occasionally expressing more data visually than sonically or vice versa). A variant of the infrared spectroscopy software developed in Universidade Nova de Lisboa in which the audio

accompanies an image of the spectrum while indicating which part of the image is being mapped sonically may be a more effective tool for students who are not visually impaired than a standalone image or, in the case of the original software, a substituted audio track. Vickers supports the combined use of visual and auditory representations by suggesting that individually, both modalities are useful for understanding, but an audio track overlapping an image of a graph may make certain patterns more easily noticeable, and the image may provide the context of the data in the sense that it demonstrates the "big picture," whereas standalone audio cannot successfully provide a useful "snapshot" of an array of data.

Brown and Hershberger have demonstrated this concept well in the field of programming. In an application used to teach bubble sort, a simple but somewhat hard-to-conceptualize sorting algorithm, Brown and Hershberger utilize several sources of sound to complement and reinforce the visual displays, primarily by conveying patterns and signaling errors in sorting. Teaching only through auditory means is very distant from the status quo, and is expected to remain so, corresponding to the reconsideration of the meshing hypothesis. However, programs that utilize auditory methods in conjunction with visual data as a means of teaching are more commonplace and continue to grow in numbers (Brown & Hershberger, 1992).

2.1.4 - The Importance of Aesthetics

One facet of data sonification that varies greatly from one program to another is that of aesthetic considerations, or considerations for whether or not the resulting audio (or music in many cases) will be manipulated to sound more pleasing to the listener and, if so, how heavily developers value aesthetics over raw data representation (Vickers, 2004). Naturally, aesthetic details should not be prioritized before the software is able to function properly as intended, but

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the aesthetic quality of any software is typically the most memorable aspect of the user's interface. One could argue that raw data mapped directly to sound is the most useful method for presenting auditory data, while equally valid arguments exist supporting the customization and personalization of this data into more aurally pleasing compositions. The Protein Music application is intuitively mapped, as only one of four lead notes can be produced with one note assigned to one nucleotide, but data such as that produced from IR spectra often generates very large sets of values that account for a drastic range, so unless only a fraction of data is represented or unless the range of values is scaled drastically, direct pitch-mapping would assign individual notes that are microtonal (and seemingly atonal) when played in sequence. Though this raw sound, electronically coded into MIDI files (which contain numerical representations of notes to be synthesized) may be the most accurate aural representation possible in terms of data sonification with little polishing needed, it may seem unsettling or directionless, which could negatively impact how well users learn from the data.

Tjeerd Andringa and J. Jolie Lanser, in a study regarding the cognitive effect of annoying sounds, assert that while pleasant sounds (i.e. sounds of nature, a baby's laughter, music) promote tranquility and allow the listener to fully control their state of mind, annoying sounds (i.e. people screaming, cars revving their engines) force listeners into a state of vigilance, with neutral sounds neither promoting nor hindering tranquility (Andringa and Lanser, 2013). These researchers, both of whom specialize in cognitive engineering, suggest that the "enhanced mind," characterized by control over mental states and the ability to easily direct attention, result from necessary mental tranquility, which is hindered by the presence of annoying or unpleasing sounds. From this, it can be concluded that raw data mapped onto MIDI may be counterproductive in terms of teaching most concepts. Depending on the range of MIDI values

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assigned to represent data, a developer runs the risk of mapping data in a range typically considered unpleasant to the human ear. Spikes in data that lead to local maxima, when represented as shrill or unsettlingly high notes, may trigger an unsolicited emotional response from the listener. The amygdala, found in the temporal lobes of the human brain, is responsible for emotional recollection, linking episodic memory with emotions experienced when the memory was formed (Royet, Zald, Versace, Costes, Lavenne, Koenig and Gervais, 2000). Though the amygdala's response to displeasing synthetic tones is mostly speculative, developers risk negatively reinforcing the principles being taught by provoking feelings of annoyance, negatively impacting students' appreciation of the music and hindering the learning process. Most evidence suggests that, for qualitative effects, a software developer should customize the musical data they are provided to create a song with a distinct melody, though not necessarily complicated, that does not represent styles that are otherwise inaccessible to the listener. The assertion that the music should have a distinct melody is based on studies that demonstrate subjects' preference towards melodic contour, which many regard as sounding more distinct and memorable than rigid ascending or descending scales, and the latter assertion speculates that, because composers "organize music according to defined structures, schemes, or sets of 'rules,'" sonified data structured in a similar way may pave the way for catchier music that promotes sooner recognition and memorization of the data presented (Royet et al., 2000).

2.2 - Software

The concept of digitally creating music to represent scientific data is no longer unheard of, and despite the variation in potential topics, common, principle sonification methods are often shared amongst applications that process a similar range or volume of data. However, like

aesthetics, the software that a developer utilizes to generate a product can be unique enough to set the application apart from similar applications. In the case of our desired product, custom scripts had to be written and other software had to be designed from scratch to sort this data into a usable form and sonify it as intended, resulting in a final application that is not quite like any software that the user might have seen before.

2.2.1 - Simulink

Simulink is a companion software to MATLAB created by Mathworks designed to model systems and simulate their behavior. The software uses a graphical development environment with 'block' objects that can be placed in the editor to create block diagrams of the system model. These blocks include algorithmic blocks such as addition and multiplication blocks, structural blocks such as switches and multiplexers, and many other blocks for other purposes. In addition, if there is ever any additional functionality that may be needed that is not already defined in a pre-built block, then code for MATLAB, C, and other languages can be implemented into the model to add these extra functions. After making diagrams with these blocks in order to create a model of a dynamic system, Simulink also allows the user to run simulations using these models. It provides tools for solving necessary equations and viewing simulation results in a scope or a data display (*Simulink*, 2014). By using this software, it is possible to create a block diagram to model a system for a chemical reactor, and data could be collected from a simulation using this model in order to be represented visually through Simulink scopes and later be sonified in another application.

2.2.2 - Python

Python is a scripting language that is known for being simple to read and quick to create meaningful code in. Python is known for being very versatile and portable, given the fact that it

is also able to run on multiple operating systems, and the fact that it can be expanded greatly

with the use of external libraries created by third parties for specific purposes (*Python*, 2014).

Relevant to this project, a specific Python library, termed "Mingus", is used frequently by

programmers for musical purposes. Mingus uses a theoretical approach to generating,

recognizing, and representing musical phrases, making it easy to work with pitches, intervals,

chords, scales, keys, and more in a relatively simple way, all while rigorously abiding by the

principles of music theory (*Mingus*, 2011). Also relevant to this project, a second Python library

termed "Matplotlib" is commonly used for creating graphs and plots to professionally represent

data in a way similar to how this would normally be done in mathematical software such as

MATLAB or Mathematica (*Matplotlib*, 2014).

2.2.3 - Max

Max/MSP/Jitter, commonly just called Max, is a graphical programming language,

primarily used for developing interactive music systems. The development environment for Max,

like Simulink, is graphical. 'Objects' with certain functions and arguments are placed in the

workspace and connected through 'cords.' These objects and cords form a sort of diagram that

visually represents how the program, called a 'patch' works, rather than being represented purely

through lines of code as in most programming languages. An example of a simple Max patch is

shown in Figure 1 below:
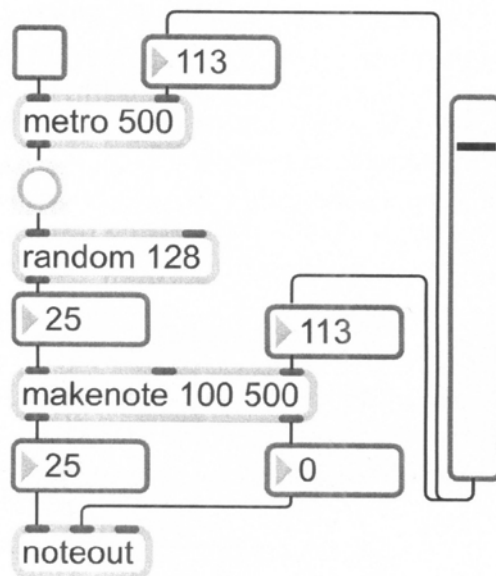
Figure 1: Sample Max patch. Various objects are connected to one another through cords (Manzo, 2011).

In addition, in some cases, these objects can be manipulated while the program is running, allowing for some interactivity within the program (Manzo, 2011). Max, being a graphical language meant for programming related to music, would be an easy choice for a language to use in creating software that needs to represent data in auditory ways. Because of this, Max is a well-suited programming language to create the software to aurally represent the data from the chemical reactor simulation.

2.3 - Chemical Engineering Concepts

Though the use of technology to create an array of learning materials that would otherwise be impractical or impossible is now commonplace in the university setting, the majority of principles and concepts that make up the chemical engineering curriculum were discovered and developed long before the invention of computers or similar modern learning tools. Unfortunately for auditory learners, modern technology has not had a universally large

impact on the fundamental way that engineering lectures are delivered, and the invention of projectors and touch-screens has only promoted the use of visual means in conveying concepts. Chemical engineering concepts are generally taught using visual learning methods: engineering components are sketched, data is plotted, and equations are solved graphically. This approach is used to convey most chemical engineering concepts with a relatively high success rate. The problem, however, is that this visual approach to problem-solving does not necessarily provide auditory learners with the tools to communicate these principles. For auditory and visual learners alike, the concepts of Multiple Steady States (MSS) and Proportional-derivative-integral (PID) control may be more easily understood with auditory methods. By adding an auditory component to visual graphs and numerical figures, we can present data in new ways to auditory learners that can better explain the underlying concepts. In this project, we will sonify the temperature and control parameters of a simulated reactor by directly mapping numerical data to musical notes.

2.3.1 - Multiple Steady States

The chemical engineering curriculum typically uses the continuous stirred-tank reactor (CSTR) concept to teach the fundamentals of MSS. We choose to follow this convention in our approach to teaching MSS. The CSTR type of reactor is commonly used in industrial processing for liquid-phase reactions. The reactor is normally operated at steady-state; hence the temperature, concentration, and reaction rate are independent of time. CSTRs are also assumed to be very well-mixed at any given time. Therefore, the temperature and concentration at the exiting stream are the same as every other point within the reactor. Figure 2 portrays a CSTR operating at steady state.
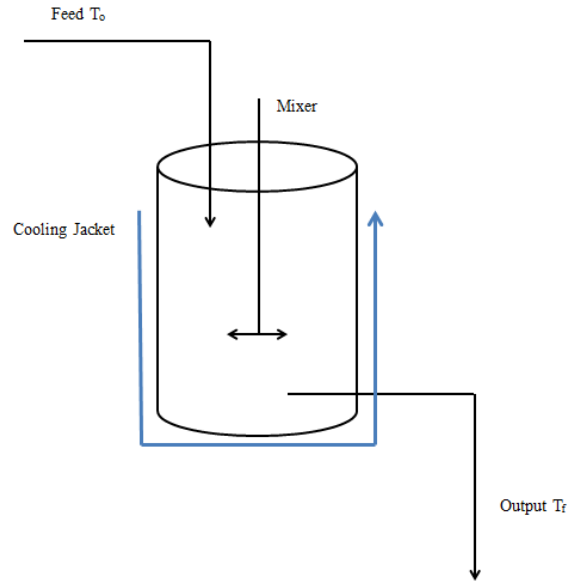
Figure 2: Diagram of the continually stirred reactor system.

At steady state conditions, the temperature within the reactor remains constant, permitting the assumption that the total energy within the reactor remains constant as well. Therefore an energy balance can indicate the relationship between the energy entering the system in the feed, the net energy of the chemical reaction, the energy escaping through the cooling jacket, and the energy leaving the system in the output flow. In many cases there is only one set of conditions that satisfies the energy balance. The system is thereby forced to converge to this set, referred to as steady state conditions, which vary from system to system. However, in multiple steady state scenarios, there are multiple unique sets of conditions that satisfy the energy balance. Therefore, the system can converge to different sets of conditions depending on its initial state.

Figure 3 demonstrates a generic energy balance within a CSTR system. The x- and y-axes represent temperature and energy, respectively, while the curve G represents the energy generated within the system. Curves A-E demonstrate the energy removed from the system at different cooling water temperatures. Each point of intersection between the heat-generated

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curve and the heat-removed curves indicate a set of conditions that satisfies the energy balance, and the system is expected to converge to one of these points over time.
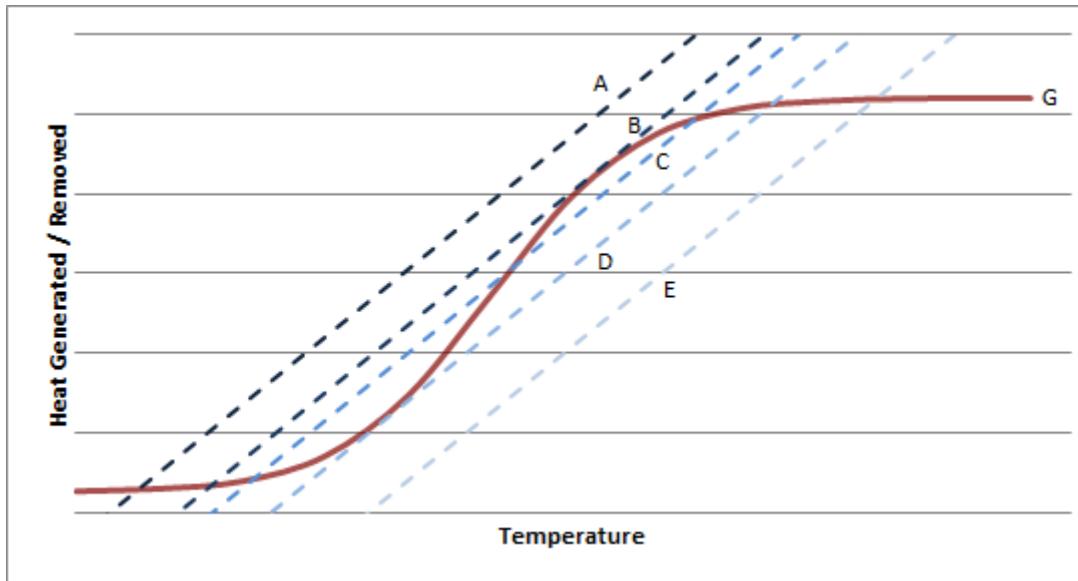
Figure 3: Energy balance in CSTR system. The curve, *G* models the heat generated due to chemical reactions. Curves *A-E* model the heat removed from the cooling jacket.

If the heat-removed curve is greater than the heat-generated curve, then the system will remove more heat than is generated and converge to its lower steady state condition. Alternatively, if the heat-removed curve is less than the heat-generated curve, then the system will generate more heat than it loses and converge to its upper steady state condition. The heat-removed curves A and E both intersect the heat-generated curve (G) at only one point; therefore, the temperature can only converge to this one point. Curves B and D each intersect curve G at two points; therefore, the reactor can operate stably at to two distinct steady state temperatures depending on the initial conditions. Curve C has three steady state conditions. The middle steady state condition is considered an unstable operating point. If the system operates at this steady state, any slight increase in temperature will result in the system converging to its upper steady state condition. Likewise, any slight decrease in temperature will result in the system converging to its lower steady state condition (Fogler, 2006). Process control can potentially be used to

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stabilize the temperature at the middle steady state condition. This method of control can add

heat or remove heat to counteract any perturbation that occurs while the temperature is at its

middle steady state.

2.3.2 - PID Control

Proportional-integral-derivative (PID) control is a form of process control that can be

utilized to manipulate the system into converging to a desired condition. In PID control, a device

measures the output of a system, then uses the measured value to change an operating value.

Figure 4 below presents a CSTR system with process control.
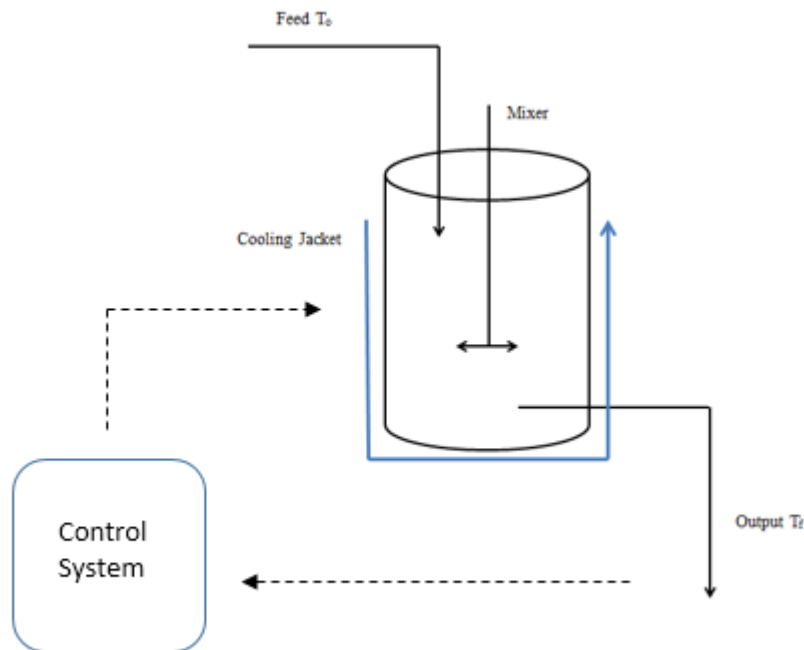
Figure 4: CSTR with control system that measures the output temperature to apply a change to
the cooling jacket temperature

In the PID control scheme, a control variable is adjusted to reduce the difference between

the actual output temperature and the desired set point temperature:

$$E(t) = T_{desired} - T_{output}$$

The error is time-dependent, meaning that the difference between the desired temperature and the output temperature will change with time. Figure 5 below presents how the error changes with time and how it relates to the desired and output temperature:
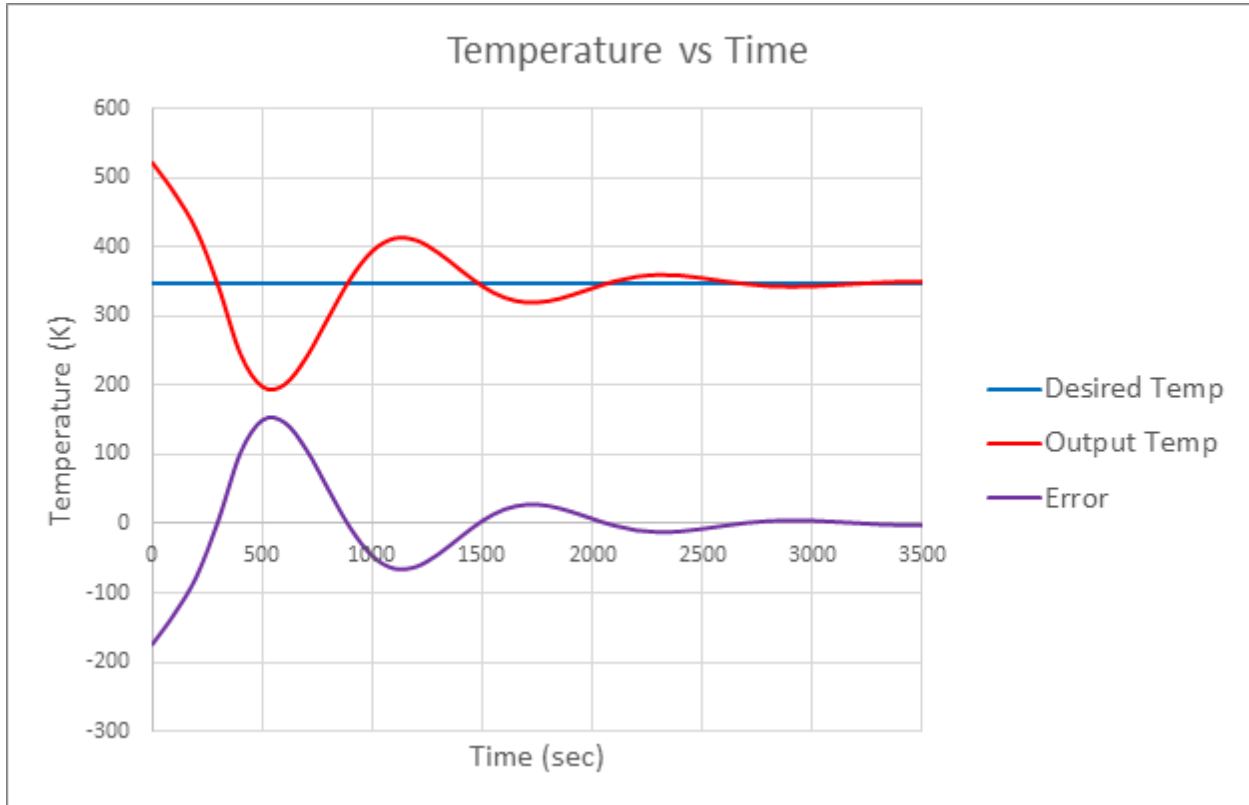
Figure 5: The relationship between the desired temperature, the output temperature, and the error.

The error is then incorporated into three separate terms, including the proportional term, the integral term, and the derivative term:

$$Q(t) = Q_o \left[K_P E(t) + K_I \int_0^t E(t)dt + K_D \frac{dE(t)}{dt} \right]$$

The term $K_P E(t)$ is the proportional term. This term takes error at each moment in time and multiplies the error by the value K_P. $K_I \int_0^t E(t)dt$ is the integral term. This term is concerned with the instantaneous error and generally has the greatest influence compared to the integral term and derivative term in PID control. This term takes the integral of the error from the initial

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point in time to the instantaneous point in time, then multiplies this integral by the value K_I. This

term accounts for all of the past errors from the start of the reaction to the instantaneous point in

time. $K_D \frac{dE(t)}{dt}$ is the derivative term. This term takes the derivative of the error and multiples this

derivative by the value K_D. The derivative term applies a heat output according to the predicted

future error and is capable of eliminating large amounts of curvature in a plot.

      In this equation, Q(t) represents the heat added to the cooling water or removed from the

cooling water at any moment in time. The temperature of the cooling water will change as heat

is added or removed from it and in turn, this cooling water affects the heat removed from the

system. The proportional, integral, and derivative terms in PID control can be seen visually with

the following Figure 6:
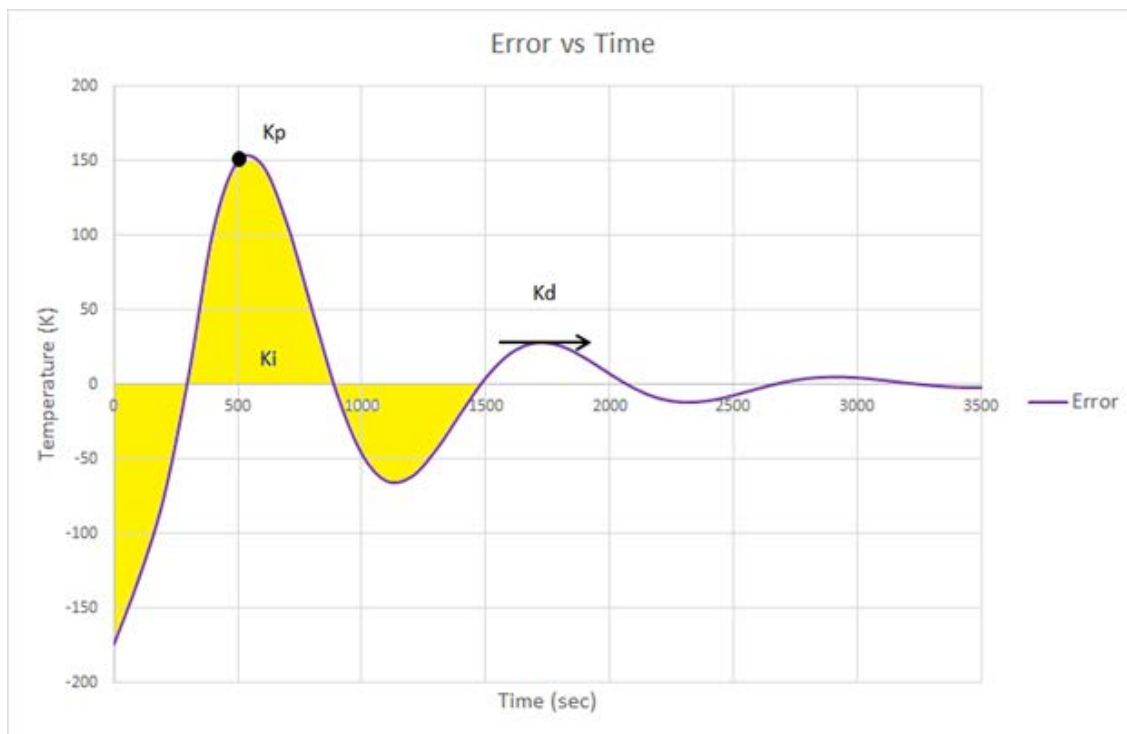
Figure 6: The function of each term in PID control

      Generally, the K_P, K_I, and K_D parameters in a PID control system are optimized to

control the temperature at the set point with minimal overshoot, offset, and oscillations, all of

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which are problems that may result from improper control over the reaction. There are several

known methods to optimize the control parameters including the *Ziegler-Nichols Tuning Method*

and the *Riggs Tuning Method*, the former of which requires the adjustment of K_P to yield a

system with sustained oscillations. The value of K_P that resulted in sustained oscillations is then

used to determine K_I and K_D. The *Riggs Tuning Method* utilizes standard method to find the

control parameters by adjusting them one at a time (Riggs, et al. 2006).

3 - Methodology

3.1 - Introduction

Our group set out to determine whether students with auditory learning preferences would learn more effectively through auditory means. To do this, we designed an assignment that incorporated a combination of auditory and visual learning. The assignment was designed to test whether the sonification data streams can help auditory learners understand PID control and MSS. The assignment consisted of four sections: a preliminary survey, background reading, a chemical engineering problem, and a post survey.

3.2 - Preliminary Survey

For the purpose of useful data analysis, it was important to have preliminary information on the learning styles of the users. To do this, a questionnaire by VARK was utilized. This questionnaire, based on answers to certain questions, gives the user relative scores for visual, auditory, read/write, and kinesthetic learning, where a higher number corresponds to a higher preference for that style of learning. Because the project is so heavily based on auditory learning, it is important to note whether or not the user is considered to be an auditory learner prior to completing the assignment in an effort to see if the project appeals to its target audience effectively. More information about the types of questions asked is contained in the Appendices.

3.3 - Modeling the Problem in Simulink

The purpose of this assignment for the students was to change the K_P, K_I, and K_D parameters in a PID control system to converge the temperature from the upper steady state condition to the middle steady state condition. The students were guided through the *Riggs*

Tuning Method to find appropriate values for K_P, K_I, and K_D. To design this assignment, we needed to model a CSTR in Simulink. The CSTR was considered to consist of three regions: the heat gained by the chemical reaction, the heat removed by the cooling water, and the PID control system.

3.3.1 - Heat Gained by Chemical Reaction

First, a CSTR was modelled in Simulink without a control system. The model accounted for the heat gained by a chemical reaction and the heat removed by cooling water. The heat gained by the chemical reaction was based on the following equation for a first-order exothermic reaction:

$$G(T) = \frac{-\Delta H_{rxn}\tau A e^{-E/RT}}{1 + \tau A e^{-E/RT}}$$

In this equation the heat of reaction is a function of temperature. The kinetics of the reaction are incorporated through A, the pre-exponential factor of the reaction and E, the activation energy of the reaction. τ is the residence time, or the amount of time that each atom spends within the reactor before exiting in the output stream. All of these variables, besides, temperature, can be considered constant for a particular CSTR system. We determined parameters that result in a relatively low amount of curvature. The low amount of curvature resulted in a small difference in energy between the heat generated curves and the heat removed curves at the middle steady state temperature. The small difference in energy allowed for the middle steady state temperature to be reached more easily with process control. The curvature in the G(T) equation was decreased by decreasing the values of τ the residence time and E, the activation energy. There needed to be some curvature, however, to make the inclusion of three steady steady temperatures possible. The values of the parameters for the system can be seen in Table 1 below:

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Parameter	Value
Delta H	57739.2
τ	0.06
A	4E9
E	56902.4

Table 1: Values for Heat Gained

G(T) can be seen as a function of temperature in the following Figure 7:
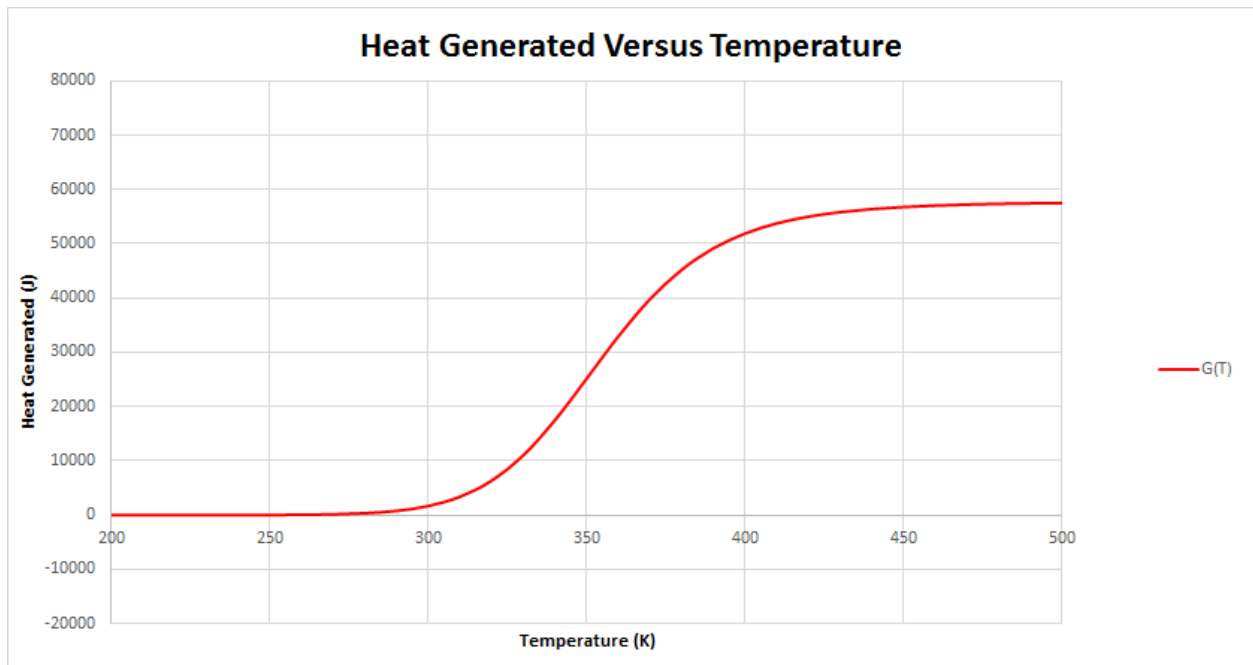
Figure 7: Heat generated as a function of temperature with the chosen values from Table 1.

These parameters were input into Simulink using blocks for addition, multiplication, and

exponentials, as in Figure 8 below:

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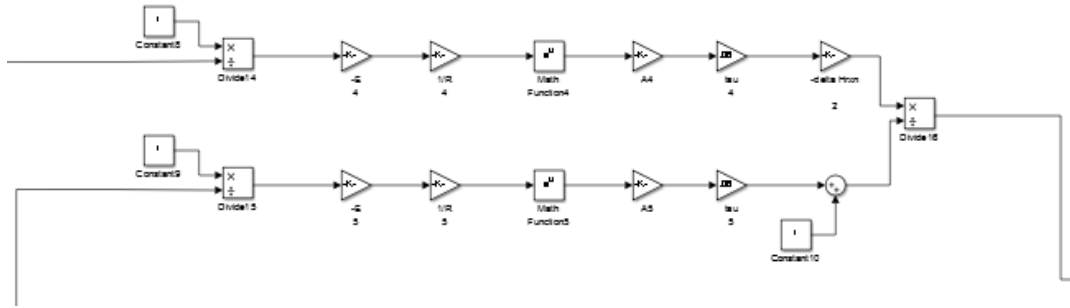
Figure 8: Sequence of blocks in Simulink to model heat gained from the chemical reaction.
This sequence of blocks used the CSTR temperature for each moment in time to calculate the
heat gained by the chemical reaction for each moment in time. The heat gained by the chemical
reaction was assumed to heat the material in the CSTR.

3.3.2 - Heat Removed by Cooling Water

Next, the heat removed by the cooling water was modelled in Simulink. A cooling jacket
containing flowing water surrounded the CSTR. The cooling jacket removed heat from the
system corresponding to the following equation:

$$R(T) = C_{P0}(1 + \kappa)(T - T_C)$$

$$where: \qquad \kappa = \frac{UA}{C_{P0}F_{A0}} \qquad T_C = \frac{T_0 + \kappa\, T_a}{1 + \kappa}$$

In this equation, the heat removed from the CSTR is a function of the CSTR temperature, T. It
also depends on the cooling water temperature, T_a. The value T_c can be viewed as a
mathematically modified cooling water temperature based on the overall heat resistance of the
reactor, which is quantified with κ. All of these variables besides temperature could be
considered constant besides the CSTR temperature, T and the cooling water temperature, T_a.
The values of the parameters were chosen to yield a line that resulted in three steady state
temperatures. The values of the parameters can be seen in the table below:

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Parameter	Value
UA	3400
Cp	300
F	30
Ta (initial)	288.15

Table 2: Values for Heat Removal

As seen in the table, an initial cooling water temperature of 288.15 K was chosen. The cooling

water temperature varied due to a PID control system, as described in a later section. The graph

of the heat gained by the reaction and the heat removed by the cooling water can be seen in

Figure 9 below:
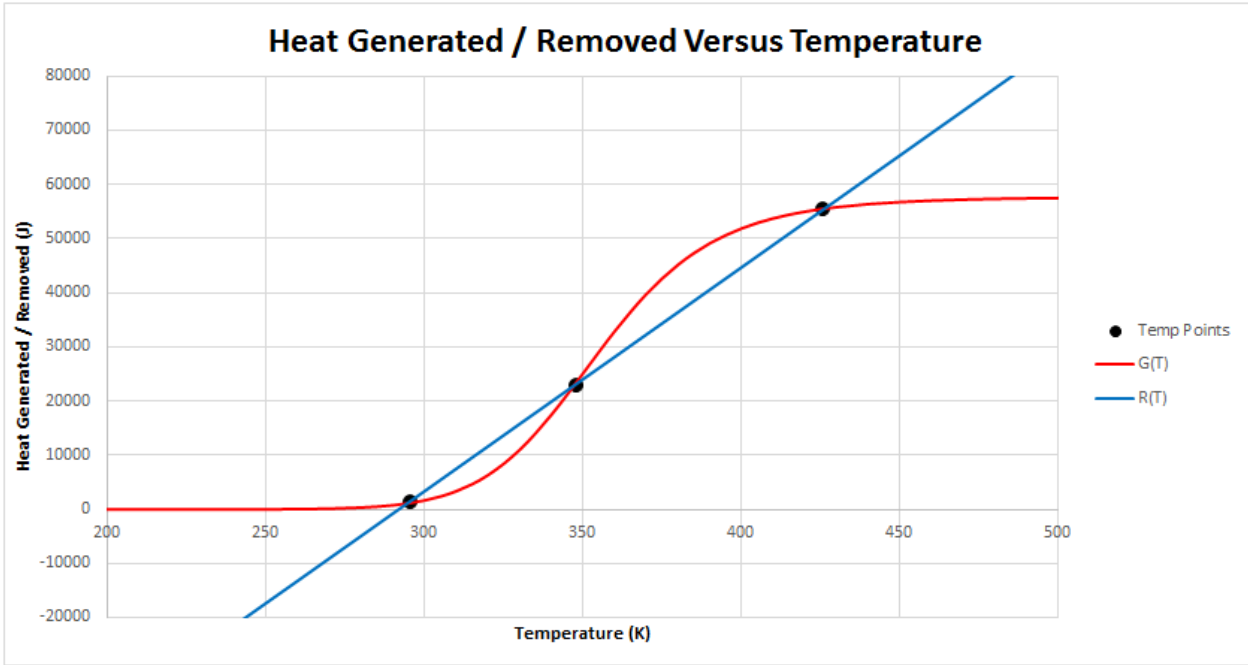
Figure 9: Heat removed plotted with the values from Table 2. The black points represent points
of steady state.

The heat removed was implemented in Simulink using blocks for addition and multiplication, as

in Figure 10 below:

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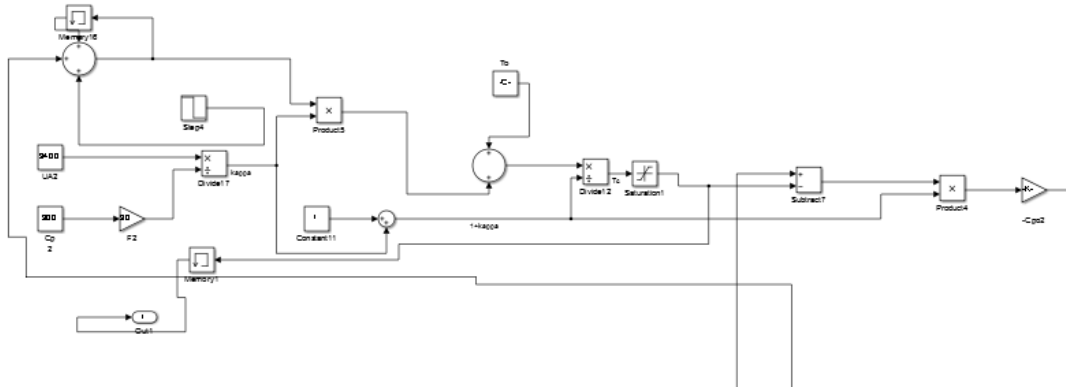
Figure 10: Sequence of Simulink blocks to model heat removed by the cooling water

This sequence of blocks resulted the heat removed by the cooling water for each moment in time.

Memory blocks were used for the temperature of the cooling water to accumulate through time.

The amount of heat removed lowered the CSTR temperature.

3.3.3 - Variable Middle Steady State Condition

Since the cooling water temperature within the PID control system was a variable, the

middle steady state temperature was not constant. This can be seen in Figure 11 below:
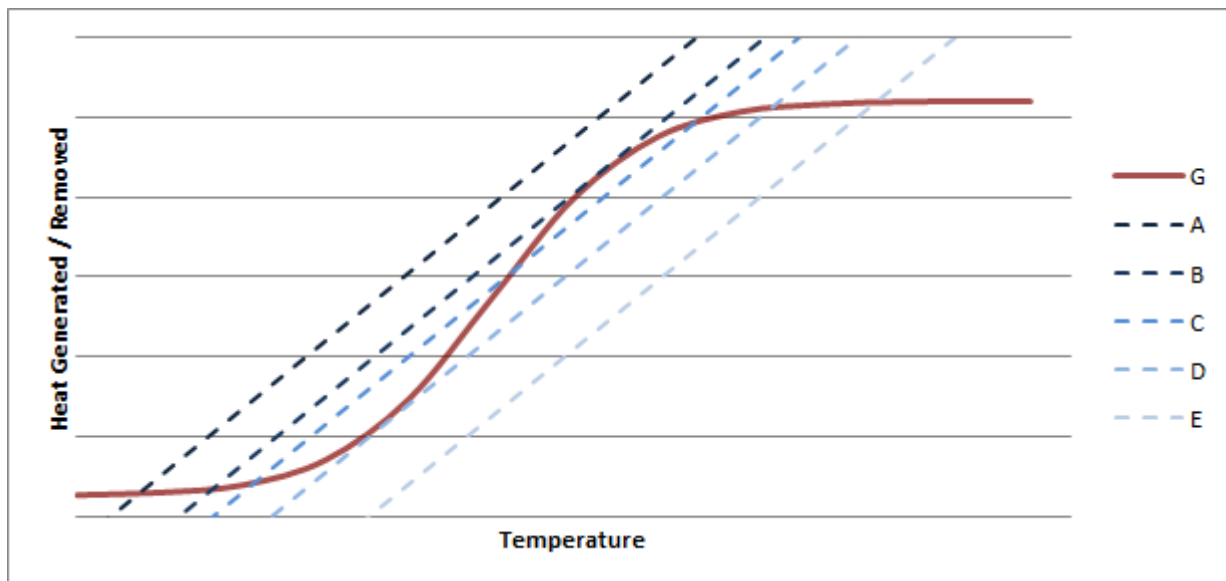
Figure 11: As the temperature of the cooling water changes, the middle steady state temperature changes as well.

As seen from the figure, different cooling water temperatures (A-E) result in different middle

steady state conditions. Due to the complexity of the PID controller algorithm and its

dependence on the student-submitted K_P, K_I, and K_D values, the value of the middle steady state

temperature could not be easily predicted. This added further complication to the system; the

control system could not converge to the middle steady state temperature if the middle steady

state temperature was not known throughout all points in time.

In order to converge the temperature to a middle steady state condition, the middle steady

state temperature was made to be a function of the cooling water temperature. The steady state

temperature corresponds to the temperatures where G(T) and R(T) are equal. Therefore the

middle steady state temperature can be found with the following equation:

$$G(T) = \frac{-\Delta H_{rxn}\tau A e^{-E/RT}}{1 + \tau A e^{-E/RT}} = C_{P0}\left(1 + \frac{UA}{C_{P0}F_{A0}}\right)\left(T - \frac{T_0 + \kappa\, T_a}{1 + \kappa}\right) = R(T)$$

It is complicated to solve the temperature as a function of the cooling water temperature and

implement the result in Simulink. Instead of finding the temperature as a function of cooling

water temperature analytically, it was chosen to find the function numerically. We used Excel's

Goal-Seek functionality to set the difference between G(T) and R(T) equal to zero. Next we

inputted different values for the cooling water temperature and Excel's regression found the

value for a temperature where G(T) and R(T) were equal. The initial guess for temperature was

important since certain cooling water temperatures yielded three steady state temperatures. The

initial guess for the temperature was chosen so that Excel's regression would converge to the

middle steady state temperature. After finding the middle steady state temperature for various

different cooling water temperatures, the middle steady state temperature was plotted against

cooling water temperature. The correlation between the two variables was linear and was

described by the following equation:

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$$T = 1.18T_C + 691.2$$

This equation was not valid over the full cooling water temperature range. Therefore, the Saturation block in Simulink was used to restrict the cooling water temperature over a valid range. This could potentially produce error if the control parameters were tuned very aggressively.

3.3.4 - PID Control System

In the Simulink model, a PID control system was used to converge the system to the middle steady state condition. The control system measured the reactor temperature, T to change the cooling water temperature, Ta. First, the error in temperature was found by subtracting the instantaneous middle steady state temperature from the instantaneous CSTR temperature. The error was then incorporated into three separate terms: the error was multiplied by K_P, the integral of the error was multiplied by K_I, and the derivative of the error was multiplied by K_D. These three terms went through an eight second transport delay block to simulate lag time in a reactor. The sum of the three heat outputs was applied to the cooling water to change the temperature of the cooling water. The new temperature of the cooling water resulted in a new CSTR temperature, which resulted in a new error in temperature and the cycle would continue until the CSTR temperature was equal to the middle steady state temperature.

We chose to present data streams of the difference between the CSTR temperature and the middle steady state temperature to make the material easier to understand for the student. The control system was implemented in Simulink using blocks for addition and multiplication as seen in Figure 12 below:
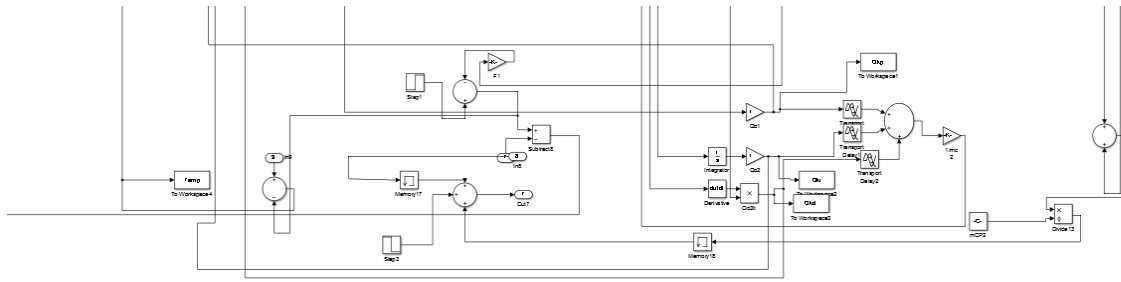
Figure 12: Sequence of Simulink blocks to model PID control system.

This sequence of blocks converted the heat of reaction and heat removed into the change in temperature of the CSTR. Therefore the temperature of the CSTR was known throughout all points in time. This sequence of blocks also found the middle steady state temperature through all points in time based on the cooling water temperature. The error between these two temperatures was input into an integration block and derivative block and then through respective control parameter blocks. The PID control system changed the temperature of the cooling water.

3.4 - Formatting the Data

After the data is produced by the Simulink simulation, it is not immediately ready to be sonified in Max. The Simulink simulation 'Simulation.slx' and the Max file 'Sonification.maxpat' must be placed in the same folder so that all of the data that is produced by the simulation can be saved to this folder and be easily accessible by the Max file. The data that is produced by the simulation is sent in arrays into the MATLAB workspace in a format that can only be read automatically in MATLAB. This data needs to be converted properly into a text file that can be read outside of MATLAB. A MATLAB script called 'Converter.m' was written for this conversion. To properly save the data to a file, all of the data arrays in the MATLAB workspace, which are represented as column matrices, need to be transposed so that they are row

matrices. This is simply a conversion that MATLAB requires to satisfy syntax requirements. After this, all of these row matrices need to be saved to a text file, which is done with the save function built into MATLAB with a parameter indicating that the output should be in ASCII format. 'Converter.m' performs this transposition of the data matrices and utilizes the MATLAB save function to output all of the data properly to a text file called 'raw_data.txt.' The 'Converter.m' script can be found in the Appendices.

The 'raw_data.txt' file is closer to being readily usable by Max, but there are a few things that still need to be changed. In Max, there is a storage object for data information. One useful aspect of the storage object is that it can be told to load a text file with a specific name as soon as Max is opened. It does so by accepting a text file and reading through each individual row of data in this file. This allows for a text file containing data from the Simulink simulation to be automatically opened and ready to be sonified upon opening Max. The data, however, must be formatted in a specific way, with spaces, commas, and semicolons in the correct locations on each row. If the data are not formatted in this way, the storage object will not be able to read it. As 'raw_data.txt' does not conform to the appropriate format, the Max storage object would not be readily able to read this data, and further steps must be taken to format the data.

To change the data into a form that can be read in automatically by the Max program, a Python script called 'Formatter.py' was written to format the data properly. Three specific tasks need to be completed in order to format 'raw_data.txt' into text files that can be read by Max. For one thing, all of the numbers in 'raw_data.txt' are represented in strings in scientific notation, with the character 'e' separating the coefficient and the exponent. Some parsing and basic calculations need to be performed on each number in data in order to properly change them to numbers in decimal form. Secondly, the data in 'raw_data.txt' is in column format, whereas

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the Max storage object reads data in rows, so this formatting needs to be performed. Finally, the data does not have the proper separation through spaces, commas, and semicolons that the Max coll object requires, so these need to be inserted. 'Formatter.py,' which is in the same folder as 'Simulation.slx,' 'Sonification.maxpat,' and 'raw_data.txt' performs all of these operations on the raw text file when opened, and it outputs five text files as a result, all of which can be read by Max. The files are 'formatted_data.txt' which contains the data for temperature and all PID control parameters, and 'T_data.txt,' 'P_data.txt,' 'I_data.txt,' and 'D_data.txt' which all have only one of the four output values of the simulation. The 'Formatter.py' script can be found in the Appendices.

3.5 - Sonifying Data

The creation of the Max component was heavily altered throughout the development of the software as features were added or altered to accommodate any range of data that might be imported. The graphical programming language Max is comprised of distinct, self-contained "objects" wired together in a practical sequence, allowing revisions to be made by simply redirecting "cords" to different or, in some cases, more objects, with minimal need for text editing. When the mechanics of the patch were finalized, all initial numerical settings and input variables were saved as presets. Because of this, when a user of the software saves their results obtained from Simulink, the data is saved in the Max component upon opening. As a final step, the visual layout of the completed Max component was drastically rearranged to hide the mechanics (including most objects and all cords), for the dual purpose of preventing a user from unintentionally editing parts of the software that would compromise its functionality and presenting the patch in a way that makes it look professional and seem less complex and

intimidating, only revealing buttons, switches and user inputs that the software user is intended to use and alter.

Though the use of quantifiable objects and the ability to change their parameters provide the programmer (and anybody observing the exposed programming) with a visual component, allowing people to understand how the software operates using common logic without learning complex programming languages, the choice to program this piece of software using Max stems from the language's vast capabilities regarding music and interactive media production. Max's predisposition to multimedia has made it a popular programming language amongst designers of musical synthesizers, sound effects, and many small-scale applications. The language has proven itself capable of recognizing, processing and analyzing data of various ranges, and though these values can be input by a user, generated from an object upstream or taken from a text file in the same folder as the patch, all objects functioning based on changeable numbers use the same standard format, meaning that the data output of any object, if input into any other object, could be interpreted by the latter object. Many objects interpret data, but the details of such interpretations vary extensively from one object to another, meaning that the same set of data destined for analysis could be used for mapping values to pitch or for assigning different threshold values that trigger an on or off message based on the incoming values. In practice, the final Max patch was made to perform all three of these tasks, achieving the intended goals of the software.

Though some objects are capable of accomplishing many tasks, objects are often more valuable when connected to one or more others, arranged in such a way that the grouping of objects can perform a more specialized, complex task than any one object individually. The Max component of the software was designed using several specialized clusters of objects, each

constructed to interpret data and ultimately use it to control a different attribute of a short song such as the range of notes played or the volume of backing instruments, determined by data calculated in Simulink. In its saved state, the patch contains a complex infrastructure of interconnected objects. Most of these objects initially await input in the form of one or more numbers, a "bang" message (one quantifiable message instructing an object to do something) or an on/off message, while the remainder await object-specific messages that are manually input by a user or output from another object. A "bang" or on/off message rarely triggers the same response in two different objects, and both of these messages are commonly output from other objects.

The first of these to take effect upon opening the software, before the user is able to manipulate any functions, include objects responsible for storing presets throughout the patch (i.e. numerical and "bang" messages that are specific to several objects) and objects responsible for recalling stored presets, distributing these messages to prepare the patch for operation. Some objects used to recall presets (saved within the patch) are also capable of importing external files located in the same folder as the software, allowing the Max component to load, display and interpret text files generated from Simulink, as well as audio files recorded in GarageBand, automatically upon the patch being opened. These particular objects are needed to recover the text files produced in Simulink detailing temperature and several heating values with respect to time, after they've been formatted in Python and saved in the same folder as the Max patch. Once recovered, each of the four text files is loaded into a separate storage object, each with the ability to recall data points from its stored set in pairs of X and Y values (representing time and the dependent variable such as temperature, respectively).

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Upstream from each storage object, an identical cluster of objects functions like a complex metronome: An on/off trigger starts the metronome at a fixed tempo and each beat sends a "bang" message to all objects downstream of the metronome, keeping a running count of each beat until the user triggers it to stop, at which point the counter will reset to zero beats and the metronome will cease to trigger any further "bang" messages until it is restarted. When in use, all four metronome systems are kept in sync while each feeds information to a separate downstream storage object, providing both a bang message and an integer (representing the number of beats elapsed) simultaneously, to be triggered at a regular interval (i.e. every beat). This integer is input into each storage object as an independent X value (representing time in seconds), and each bang message triggers the storage object to recall the corresponding Y value for the given X input. Though the functions of these objects and the communication between them is complex at a small scale, this cluster of objects (occurring four times throughout the Max component) performs an easily summarized task: Taking results (for the temperature and each PID control parameter) generated in Simulink and, after an on/off message is triggered, outputting all generated values individually in order of time.

This steady stream of data is then fed through several objects which scale all values to a smaller range, shift their numerical value up or down, and round all data points to fit into the key of C major by removing numerical values that translate to musical notes not found within the key. (While all scaled data is fit into C major, the degree to which data points are scaled and shifted is different for values of temperature and each PID control parameter so that once these values are sonified, they all occupy a similar range of notes, providing a sense of consistency for the user and allowing them to objectively listen for trends and subtle or dramatic changes.) Since incoming data is scaled and shifted almost instantaneously, the time-dependent data (output from

the metronome cluster of objects) is matched by a similar stream of values representing the same trends and behavior that can be sonified directly. The stream of data enters a cluster of objects responsible for truly sonifying the data by pitch-mapping each incoming value in real-time, audibly outputting corresponding notes in a MIDI trumpet tone with each note beginning and sustaining at a constant volume. Due to the scaling and rounding of data, many rapidly changing values from Simulink can potentially translate to a single note if the values all within a short range, so a small feature is added to the patch sustaining any note that is triggered more than once, resulting in a note being held and not rapidly accentuated should such a situation occur. This cluster is identical for all four sets of data, and a drop-box object is included to allow the user to choose whether they would like to listen to the temperature or any of the three PID control parameters.

To further engage users, the software includes multi-tracked background music, containing pre-recorded drums, guitar, bass, piano, strings, oboes and flutes, all taken from an external folder and saved to their correct object when the patch is initially opened. These tracks do not change and therefore play in a fixed key and tempo, though the patch is equipped with a large cluster of objects responsible for controlling the volume of each instrumental track. The particular collection of instrumental tracks playing at a given time is intended to demonstrate the simulation's stability with respect to temperature at a given time. Though the user may listen to temperature or any PID control parameter, the temperature values output from a metronome cluster is fed into a series of objects and met with several conditional objects that test the value against a range of integers. These conditional objects are each assigned a different range of integers above and below the desired temperature and are intended to overlap one another. At any given time, when the incoming temperature value falls into the range assigned to one

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instrument (the guitar, for example), the volume of that instrument track will quickly but gradually increase from zero to a maximum value (that is quiet enough to not drown out the pitch-mapped trumpet melody) and maintain this volume until the temperature falls out of range, at which point the instrument track will gradually return to zero.

When individual tracks are silent, they are simply playing with the volume shut off so that if and when they are heard again, they are synchronized with all other instruments. The standard mechanism applies to all instrumental tracks except for the drums, which are constantly heard regardless of the temperature value. The others operate with a fixed range, and this range becomes increasingly less broad for each instrument. Therefore, if the value tested against each range began at an arbitrary point far below the desired temperature and increased at a constant rate, the user would hear only the sonified integer and drums until the value met the minimum range for the guitar, at which point they would hear the guitar as well. This would repeat, in order, for the bass, piano, strings and oboe, and only once the desired value is met, the flute would play, resulting in all instruments accompanying the melody. If the value continued to increase steadily, the flute track would return to no volume and all other instruments would follow suit until, once again, only the drum track and sonified integer would be heard. Due to this system, the user can consciously pick out the relative value of whatever parameter they chose based on pitch as well as the simulation's thermal stability based on the collection of background instruments being heard.

The complexity of the patch, with regards to the large number of objects and the intricacy with which they are interconnected, could potentially be unappealing or intimidating to a student hoping to use this software as a learning tool. However, Max contains a number of features allowing the programmer to keep their work organized. While most of these features are in place

to hide objects or cords during construction to reduce messiness or distraction, one of the most commonly used features is "Presentation Mode," in which all cords are hidden and the programmer chooses which objects will be visible to the user, as well as their placement, order and appearance, with no dependence on the linearity of objects or where and how they are linked. Because of the many factors that must be kept consistent for this patch to function properly and their reliance upon objects that are vulnerable to improper manipulation by users, the patch's design in Presentation Mode shows only twenty-four objects (though the patch incorporates over one-hundred). When the software user opens this patch after completing their work in Simulink, they are presented with a large on/off button to begin running and sonifying data, followed closely by two troubleshooting buttons (one of which will kill sustained notes and one that will force the storage objects to read new data, in the event that it was saved by Simulink after the Max component had been opened).

The remainder of the patch includes the drop-box to select temperature or any parameter to hear, a button to turn the background music on or off, and several sliders, number boxes and buttons that indicate the time and parameter values and which background instruments are playing at a given time (thereby indicating the simulation's temperature stability visually). Most of the patch operates behind the scenes but with this simplified layout, the overall work done by the Max component is easily summarized: Once open, the patch contains stored data regarding temperature and three PID control parameters as they change over time, resulting from a previous experiment using Simulink. When the largest button is pressed, whatever data selected in a drop-box becomes audible while the numerical values of all parameters (including those that are not being sonified) are displayed with time, all while a backing musical arrangement plays, gaining and losing instruments corresponding to thermal stability. Though the resulting concepts

and functionality aren't necessarily elementary, the Max component of the software is presented to users in a small, concise and fully functional application.

3.6 - Creating the Assignment

A survey was created to get user feedback on the software that was created. This survey asks questions on a scale of 1-5 (from strongly disagree to strongly agree) about the user experience with the software and its educational value. The survey and responses to the survey can be found in the Appendices. Once the software and the survey were completely finished, they needed to be given to people who would be able to properly test the software and give useful feedback for future efforts in this project. Given the nature of the educational content of the software, it could be best assessed by chemical engineering students at the undergraduate level. To ensure a high participation level, it was determined that the most effective way to validate the project was to present it in the form of an extra credit assignment in the "CHE 3301: Introduction to Biological Engineering" class taught by Professor Timko, one of the advisors for this project. This class is applicable to the content of the assignment, since a lot of the subject matter is relevant to the topics of PID control and MSS. By successfully completing this assignment and submitting a survey response, a student in this class would be given extra credit toward their final grade in the course, providing adequate incentive for a user to test the software.

An assignment was formed by creating a document with background reading material and a set of instructions to follow in using the software from Simulink and Max. First, the assignment instructs the user to take the VARK Questionnaire and note down the results from this to determine his or her supposed learning style. This is done to determine whether the student is an auditory learner, as this is most pertinent to the project at hand. Then, the user is presented content about PID control and MSS through reading background material on the subject. After

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having an opportunity to become more knowledgeable about the subject matter, the student is guided through a set of instructions on how to manipulate the parameters in Simulink, how to properly format the data, and how to sonify the result in Max. The student is told to record results for the control parameters in Simulink to verify that they were able to successfully complete the assignment. Finally, the student is told to complete the survey in order to validate their user experience with the software. The document with background material, the instructions, and the survey can be found in the Appendices.

To properly complete the assignment, the students would need to be given access to computers that have MATLAB, Max, and a Python interpreter installed. None of the computers on the WPI campus have all of this software readily installed, so all of this software was installed on each of four laptops that were borrowed from the Academic Technology Center (ATC). These laptops were then stored in the office of the Department of Chemical Engineering at WPI to be rented out by students who intended to complete the assignment, during normal business hours, until the due date of the assignment. The documents and resources necessary for the assignment were posted online in order to be readily accessible by the students from these computers. With all of this preparation complete, students were able to successfully complete their extra credit assignment and provide meaningful feedback for the project.

4 - Results and Discussion

The assignment was designed to test whether the sonified data streams helped auditory learners understand PID control and MSS. Using data from 23 students for the preliminary survey and the post survey, we plotted the helpfulness of the auditory component of the assignment against the students' capacity to learn by auditory means, as determined by the VARK preliminary survey. The results are shown below in Figure 13.
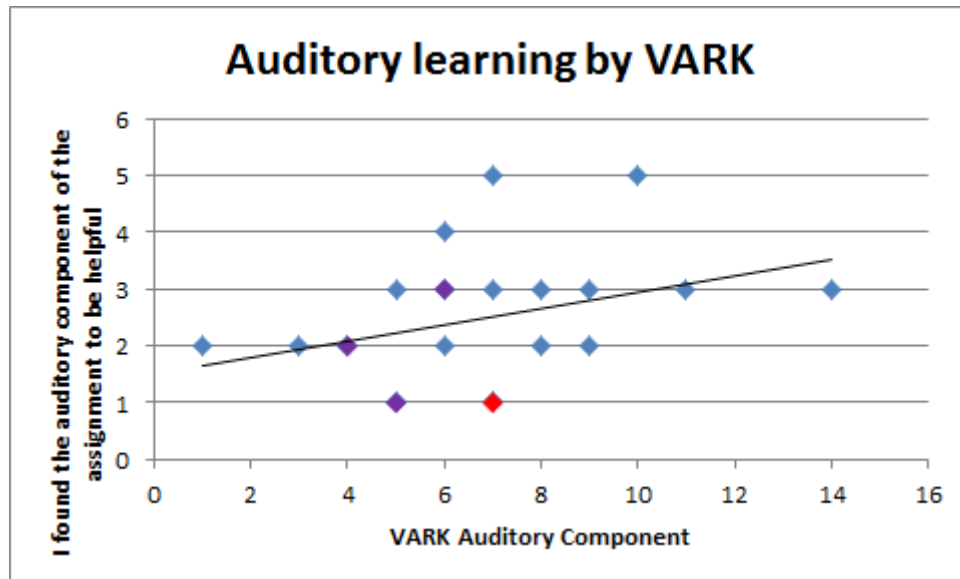
Figure 13: Plot showing the trend that the auditory component of the assignment helped auditory learners learn the material. The blue points represent one student, the purple points represent 2 students with the same scores, and the red point represents 3 students with the same scores.

The figure depicts the general trend that the sonification of the data streams helped students with a preference to auditory learning. This data supports the claim that sonification of data has potential to help auditory learners understand engineering principles. The Likert-Scale produced ordinal. This data type consists of a ranked set of numerical scores without exact numerical quantities. The mean and standard deviation are generally considered to be statistically invalid for this data type. Rather, the median and mode are more appropriate for statistical analysis. The median and mode values for the VARK auditory score were each 7. The

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median and mode for the usefulness of the auditory component of the assignment were 2 and 3 respectively.

We statistically analyzed whether the scatter in the data affected our ability to make significant claims about the data. It is appropriate to analyze ordinal data with chi-squared statistics (Allen 2007). This analysis determines the likelihood that the correlation between data sets is due the random sampling distribution. We analyzed whether there was a reproducible correlation between the VARK auditory scores and the usefulness of the auditory component of the assignment. Using the Chi-squared test, we determined that there was a 42% chance that the correlation was due to the random distribution of students that took the assignment. This is far above the 5% threshold that is commonly held to make significant claims about data. There was also error in the Chi-squared test due to our low population size; the Chi-squared test is an approximation that loses its validity when the population size is small. We recommend applying Fisher's exact test on the data set to determine the correlation without mathematical approximations. This analysis cannot be done on our set of data without the aid of software packages.

Next, we plotted an analogous graph portraying the helpfulness of the visual component of the assignment against their capacity to learn by visual means. The results are shown below in Figure 14.
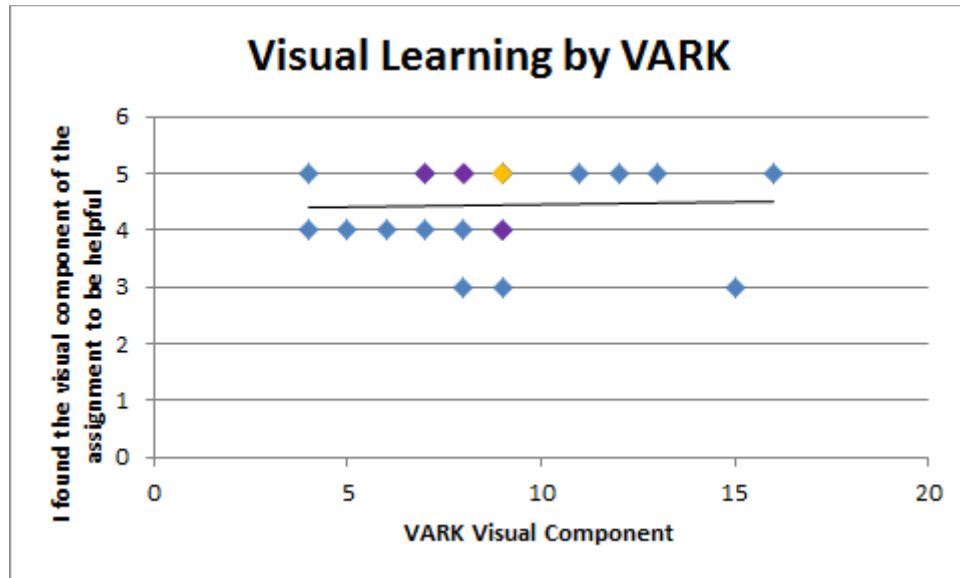
Figure 14: Plot showing the trend that the visual component of the assignment helped students consistently regardless of visual learning capacity. The orange-yellow point represents 4 students with the same scores.

Figure 14 reveals no correlation between the utility of visual components and the propensity of subjects to be visual learners. From the Chi-squared test, we determined that any correlation would have a 73% chance of occurring due to the random distribution of students. The data suggested that all students learned from the visual component consistently regardless of their capacity for visual learning. We expected there to be a positive trend between these variables. The median and mode values for the VARK visual score were each 9. The median and mode values for the usefulness of the visual component of the assignment were each 5. We determined that more students tended to be visual learners than auditory learners from the VARK survey. Likewise, students generally deemed the visual component of the assignment to be more useful than the auditory component of the assignment.

We decided that there could have been factors influencing the data other than the tendency of each student to mark answers high or low. These factors consisted of: the nature of survey data, the unclearness of the instructions, the validity of the VARK survey, whether the

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students were provided enough background information to understand the assignment, and whether each student completed the full assignment. We will present each of these factors to determine their influence on the data.

First, we evaluated the potential effect of the Likert scale survey on the scatter in data. Consistent data relied on each student marking the answer to each question with the same disposition; however this study did not necessarily achieve consistent data with our relatively small sample size. Some students may have tended to mark their answers high or low compared to other students. Due to the discrete intervals of the Likert Scale, the tendency to mark answers high or low could have resulted in the scatter seen in the figure above.

Next we chose to determine whether the clarity of our instructions affected the data. Figure 15 below presents a histogram showing whether each student found the instructions to be clear and easy to follow. The y-axis of the graph corresponds to question 3 of the post survey: *I found the instructions for the assignment to be clear.*
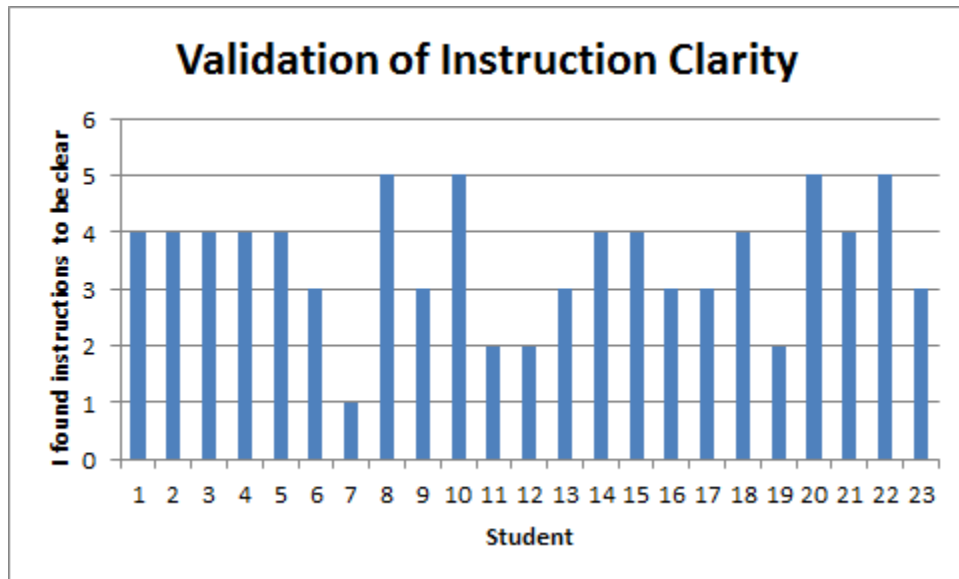
Figure 15: Histogram showing that the majority of students found the instructions to be clear.

Figure 15 demonstrates that the majority of students found the instructions to be relatively clear, providing an answer of "agree" or "strongly agree" to the question. Lack of clear instructions may have affected the ability to learn from the assignment for students 7, 11, 12, and 19. These students rated the instructions' clarity to be 2 or lower. Each of these students, however, claimed to have benefited from the software in the other survey questions. Also, these students obtained reasonable PID control parameters. We assumed that these students had difficulty with the instructions, but eventually resolved their difficulties and completed the assignment appropriately. From these data we conclude that the instructions affected the results to a minimal extent.

Next, we chose to evaluate whether the VARK survey produced agreeable data with each individual's personal beliefs of their learning preferences. Figure 16 below presents the relationship between the results for VARK preliminary survey and personal preferences. The y-axis corresponds to the survey question: *I consider myself to be an auditory learner.* The x-axis corresponds to the auditory results from the VARK preliminary survey.
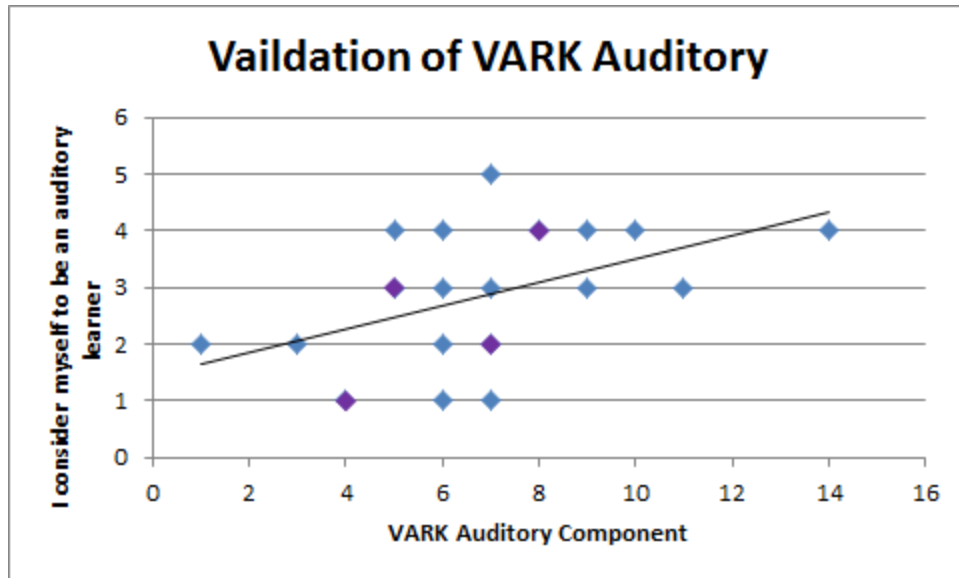
Figure 16: Plot of each student's' personal opinion regarding their capacity for auditory learning against their auditory score from the VARK survey

The figure above demonstrates that the VARK survey may produce severely different results than personal opinions. As seen in the figure above, two students considered themselves to be *5* and *1* for auditory learning, respectively, yet the VARK survey gave each of these students the same auditory learning score. The discrepancy between the VARK survey and personal opinions demonstrates that the VARK survey may be unreliable. Alternatively, some students may have underestimated or overestimated their learning preferences. The VARK site estimates that the auditory scores it produces are 82% accurate. We determined that the VARK survey was the better indicator of auditory capability. A more comprehensive preliminary survey than the VARK preliminary survey could potentially be used to evaluate auditory learning capacity in future studies.

Next, we chose to evaluate the validity of the VARK survey for visual learning. Figure 17 below presents the visual analog for the relationship between the results for VARK preliminary survey and personal preferences.

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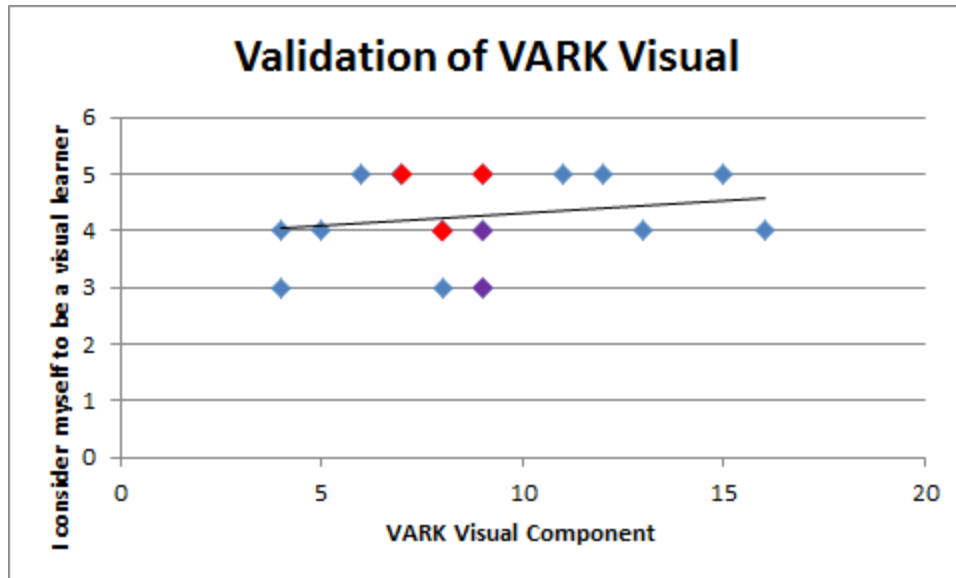
Figure 17: Plot of each student's' personal opinion regarding their capacity for visual learning against their visual score from the VARK survey.

The figure demonstrates that the VARK preliminary survey matched students' personal opinions more reasonably for visual learning than it did for auditory learning. The VARK survey estimates 85% accuracy in its visual scores.

Next, we wanted to determine if the students were presented enough background information in PID control and MSS to satisfactorily complete the assignment. We used the feedback in the comments to determine whether the background reading was helpful. We received a lot of positive feedback regarding the background information: "The background reading was useful, it helped me to understand what I am supposed to do." "I thought the introduction to PID control was very well written and explained." "One of the most beneficial things I think that helped with this assignment was providing the background reading in so many different forms. You used text, equations, and charts all very nicely, which allowed for each specific type of learning to be able to understand the material a little bit better, especially since it was brand new." We would recommend asking a 5-point Likert scale survey question about the

background material to verify that it does not affect any student's ability to learn from the assignment.

Lastly, we critically examined the PID parameters for each student to verify that they completed the assignment. One student did not change either the K_d parameter nor the K_i parameters from their initial values of zero. Another student changed K_i, but not K_d. These students did explore the software fully and did not see certain concepts, such as the spikes of QK_d heat output when the derivative was large in magnitude. The remainder of the students satisfactorily completed the project; these students changed the K_p, K_i, and K_d parameters to converge the temperature to the middle steady state condition. Many students understood to increase K_d to a very high value to eliminate the oscillation of the temperature between the lower and upper steady states. Many students also increased K_p to the 80-130 range which resulted in more ideal temperature convergences when the other parameters were set to zero. We determined that two of the students did not fully complete the assignment, which may have influenced their survey results, thus, affecting the composite results. However, the majority of the students successfully completed the assignment, submitting useful and informative feedback regarding the auditory component.

5 - Conclusions and Future Work

Based on the assignment and survey results, we were able to determine that the auditory component of our software was helpful to students who tend to benefit from auditory learning styles. A Chi-squared test yielded a 42% probability that the perceived trend resulted from the random distribution of sample students. While the auditory component of our software did not prove itself to be useful to all of the students who completed the assignment, it was deemed useful in general by the auditory learners in the group of students, who were our target audience. We also provided validation that the instructions for the assignment and the background material did not affect the students' scores for auditory learning. We found that the majority of students preferred visual learning to auditory learning based on their VARK preliminary scores and their stated personal preferences in the post survey; therefore, it is important to consider the extent that auditory learning should be used to present new course material. We recommend presenting auditory learning as an option for students, not as the primary means to teach engineering concepts.

Despite the successful results of our project, the assignment and software could be improved in the future to enhance utility and the user experience. Although most students believed that the instructions were clear, there were a few students who did not believe so. In order to appeal to the entire crowd completing the assignment and using the software, the instructions could be revised so that they are clear to everyone. In addition, some students believed that there were unpleasantly high-pitched sounds coming out of the sonification software occasionally. It is possible that fine-tuning of the range of values to be sonified could resolve this issue, placing the sounds produced by the software more within the comfortable range of pitches. Also, some students claimed that the conversion steps in between using

Simulink and Max were convoluted and a bit inconvenient. To enhance the user experience, further automation work could be done to speed up or eliminate this conversion process.

Auditory learning could also be used in different material in different age groups. It is very possible that younger students would prefer auditory learning more that undergraduate students. Younger students may have turned away from engineering because they did not enjoy its visual learning style. Presenting engineering concepts to younger students with auditory learning may attract more auditory learners to the engineering discipline.

Even though there are a few improvements that could be made to enhance our software and assignment, the project was successful in achieving its goal of appealing to auditory learners in the STEM area. It is possible that there may be more effective methods of sonification than the one that we developed for our software, but this project supports the idea that auditory learning methods can help auditory learners. There is potential to expand upon what was done in this project in the future, both in terms of scope of sonification and in terms of the various engineering disciplines that can benefit from auditory learning styles. With more research and development done for auditory learning methods in the future, auditory learners would have access to a more conducive learning environment.

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Appendices

Appendix A: Preliminary Survey

The preliminary survey used for our assignment is a questionnaire created by VARK. To view the survey and see the questions asked in it, please follow the link below:

http://vark-learn.com/the-vark-questionnaire/

Appendix B: Converter.m

```
% Transpose all workspace data arrays
t = tout';
P = Qkp';
I = Qki';
D = Qkd';
T = Temp';


% Save all transposed arrays to a text file
save('raw_data.txt', 't', 'P', 'I', 'D', 'T', '-ascii')
```

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Appendix C: Formatter.py

```python
i = 0  # Index for reading through each line of raw_data.txt

# Arrays for storing parsed data
t_data_string = []
t_val = []
P_data_string = []
P_val = []
I_data_string = []
I_val = []
D_data_string = []
D_val = []
T_data_string = []
T_val = []


# Open raw_data.txt for reading in data
read_file = open('raw_data.txt', 'r')

# Open other text files for writing formatted data
write_file = open('formatted_data.txt', 'w')
T_file = open('T_data.txt', 'w')
P_file = open('P_data.txt', 'w')
I_file = open('I_data.txt', 'w')
D_file = open('D_data.txt', 'w')

# Collect all data on each line into an appropriate array of strings
for line in read_file:
    raw_data = line.split()
    if i == 0:
        t_data_string = raw_data
    elif i == 1:
        P_data_string = raw_data
    elif i == 2:
        I_data_string = raw_data
    elif i == 3:
        D_data_string = raw_data
    elif i == 4:
        T_data_string = raw_data
    i += 1

# Split coefficient and exponent of each data element
# Store new data in arrays of values
if len(t_data_string) == len(P_data_string) == len(I_data_string) ==
len(D_data_string) == len(T_data_string):
    for a in range(len(t_data_string)):
        t_data = t_data_string[a].split('e')
        t_val.append(float(t_data[0]) * (10 ** float(t_data[1])))
```

```python
    for b in range(len(P_data_string)):
        P_data = P_data_string[b].split('e')
        P_val.append(float(P_data[0]) * (10 ** float(P_data[1])))
    for c in range(len(I_data_string)):
        I_data = I_data_string[c].split('e')
        I_val.append(float(I_data[0]) * (10 ** float(I_data[1])))
    for d in range(len(D_data_string)):
        D_data = D_data_string[d].split('e')
        D_val.append(float(D_data[0]) * (10 ** float(D_data[1])))
    for e in range(len(T_data_string)):
        T_data = T_data_string[e].split('e')
        T_val.append(float(T_data[0]) * (10 ** float(T_data[1])))
else:
    print("Error: Index and data values do not line up. Try creating data
again.")


# Write data to formatted_data.txt
if len(t_val) == len(P_val) == len(I_val) == len(D_val) == len(T_val):
    for n in range(len(t_val)):
        write_file.write(str(int(t_val[n])) + ', ' + str(float(P_val[n])) + '
' + str(float(I_val[n])) + ' ' + str(float(D_val[n])) + ' ' +
str(float(T_val[n])) + ';\n')
else:
    print("Error: Index and data values do not line up. Try creating data
again.")


# Write data to T_data.txt
if len(t_val) == len(T_val):
    for n in range(len(t_val)):
        T_file.write(str(int(t_val[n])) + ', ' + str(float(T_val[n])) +
';\n')
else:
    print("Error: Index and data values do not line up. Try creating data
again.")


# Write data to P_data.txt
if len(t_val) == len(P_val):
    for n in range(len(t_val)):
        P_file.write(str(int(t_val[n])) + ', ' + str(float(P_val[n])) +
';\n')
else:
    print("Error: Index and data values do not line up. Try creating data
again.")


# Write data to I_data.txt
if len(t_val) == len(I_val):
    for n in range(len(t_val)):
        I_file.write(str(int(t_val[n])) + ', ' + str(float(I_val[n])) +
';\n')
```

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```
else:
    print("Error: Index and data values do not line up. Try creating data
again.")


# Write data to D_data.txt
if len(t_val) == len(D_val):
    for n in range(len(t_val)):
        D_file.write(str(int(t_val[n])) + ', ' + str(float(D_val[n])) +
';\n')
else:
    print("Error: Index and data values do not line up. Try creating data
again.")
```

Appendix D: Assignment

Preliminary Survey

Before starting the rest of the assignment, take the following questionnaire by VARK about learning styles:

http://vark-learn.com/the-vark-questionnaire/

As the questionnaire notes, it is alright to select more than one answer to each question if applicable. After completing the questionnaire, write down the scores for each learning style and the learning style preference for later use.

For this assignment you will read Background information on *Multiple Steady States* and *Proportional-Integral-Derivative Control Systems*. You will then be asked to complete an assignment about these topics that utilizes visual and auditory learning. Lastly, you will be asked to complete a survey that addresses what you learned from the assignment.

Background on Multiple Steady States

The objective of this assignment is to control the temperature of a continuously-stirred-tank-reactor (CSTR) using process control. An example of a CSTR is shown below in figure 1:
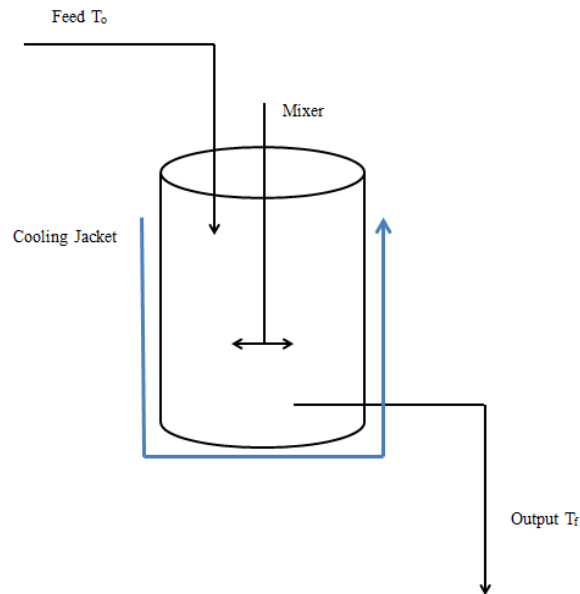
Figure 1: Diagram of a continuously-stirred-tank-reactor (CSTR)

A feed enters the CSTR at an initial temperature, T_o. Inside the CSTR, a reaction takes place to add heat to the system or remove heat from the system. The reaction in the model of this assignment is a first-order exothermic reaction, and thus adds heat to the system corresponding to the following equation:

$$G(T) = \frac{-\Delta H_{rxn}\tau Ae^{-E/RT}}{1 + \tau Ae^{-E/RT}}$$

In this equation the heat of reaction is a function of temperature. The kinetics of the reaction are incorporated through A, the preexponential factor of the reaction and E, the activation energy of the reaction. In this equation, τ is the residence time, or the amount of time that each atom spends within the reactor before exiting in the output stream.

A cooling jacket containing flowing water surrounds the CSTR. The cooling jacket removes heat from the system corresponding to the following equation:

$$R(T) = C_{P0}(1 + \kappa)(T - T_C)$$

$$\text{where:} \qquad \kappa = \frac{UA}{C_{P0}F_{A0}} \qquad T_C = \frac{T_0 + \kappa T_a}{1 + \kappa}$$

In this equation, the heat removed from the CSTR is a function of the CSTR temperature, T. It also depends on the cooling water temperature, T_a. The value T_c can be viewed as a mathematically modified cooling water temperature based on the overall heat resistance of the reactor, which is quantified with κ.

The process is considered to be at a steady state condition when the heat added to the system from the chemical reaction is equal to the heat removed from the system by the cooling water. The steady state condition can be determined by plotting the heat of reaction, G(T) and the heat removed by the cooling water, R(T) simultaneously against temperature. The steady state temperature is the temperature where G(T) and R(T) are equal. The figure below shows the steady state temperature for an arbitrary system:
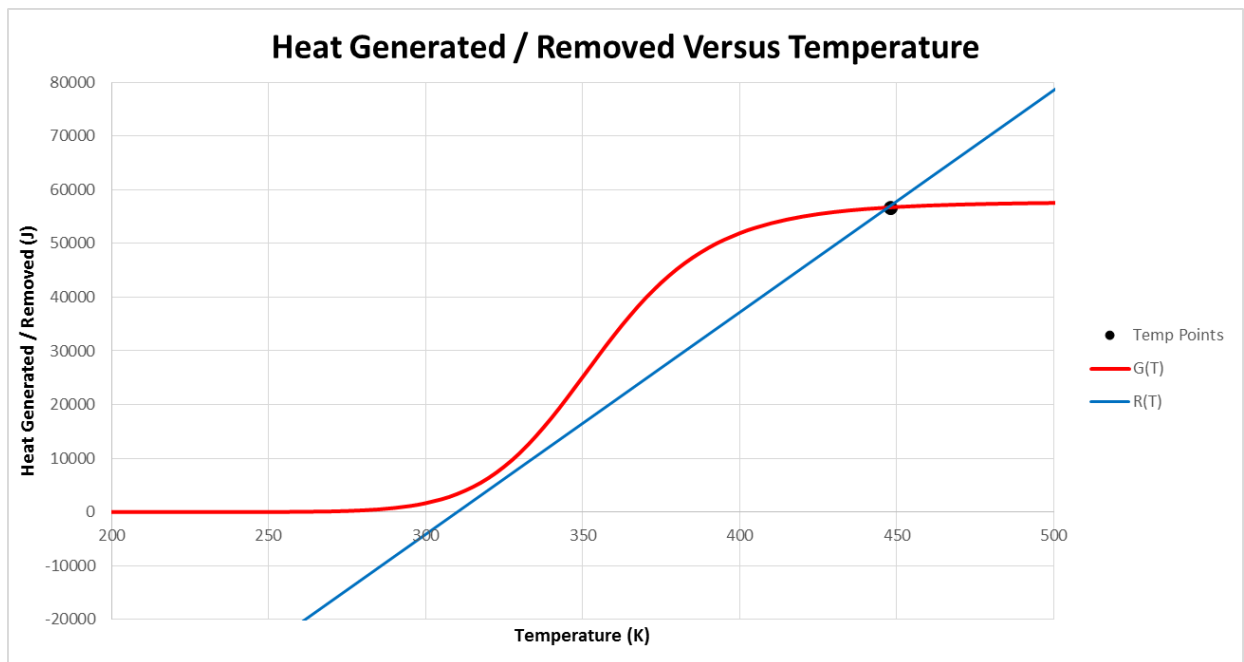
Figure 2: Plotting Heat of reaction and heat removed to find the steady state condition

At 448 K, the heat gained from the reaction is equal to the heat removed by the cooling water. Therefore there is no net gain or loss of heat, and the temperature remains constant. This temperature represents the steady state temperature. Next, consider a temperature greater than 448 K. Notice that the heat removed is always greater than the heat gained in this range of temperatures. Therefore, if the system was at a temperature of 470 K, for instance, there would be a net loss of heat until the system reached 448 K. Alternatively, at temperatures below 448 K the heat gained from reaction is greater than the heat removed. Thus if the temperature is below 448 K, it will increase until it reaches 448 K.

Many systems only have one steady state temperature; however it is possible for some systems to have multiples steady state temperatures. The figure below portrays a scenario where three steady state temperatures exist.

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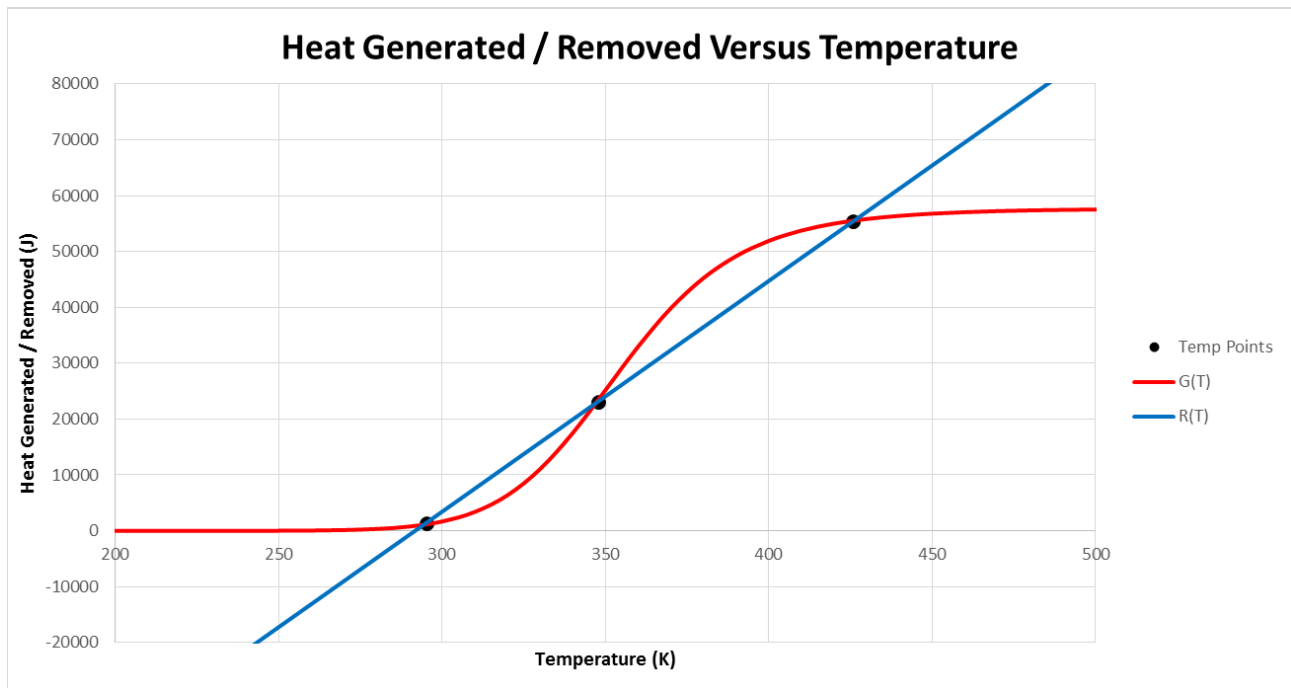
Figure 3: Plot with multiple steady states; the middle steady state is unstable

Notice that the G(T) and R(T) curves intersect at three temperatures: 295, 348, and 426 K. The heat gained from the reaction is equal to the heat removed by the cooling water at these three steady state temperatures. 295 K is considered the lower steady state temperature, 348 K is considered the middle steady state temperature, and 426 K is considered the upper steady state temperature. The lower and upper steady state temperatures are stable. Consider a temperature below the lower steady state temperature, 260 K for example. At this temperature, G(T) is greater than R(T) and thus the temperature will increase until it reaches the lower steady state temperature. Now consider a temperature in between the lower steady state temperature and the middle steady state temperature, 340 K for example. At this temperature, R(T) is greater than G(T) and thus temperature will decrease until it reaches the lower steady state temperature. Now, consider a temperature between the middle steady state and the upper steady state temperature, 400 K for example. At this temperate, the heat gained is greater than the heat removed and thus the temperature will increase until it reaches the upper steady state temperature. The middle steady state temperature is considered unstable. If the system is at the middle steady state condition, then any slight perturbation will cause the system to crash to the lower or upper steady state.

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Background on PID Control

In this assignment, we will use process control to converge the system to the middle steady state condition. In process control, a device measures the output of a system and uses that output to change an input value. In our problem a sensor will measure the output temperature, T_f and will change the cooling water temperature. The figure below presents a CSTR system with process control.
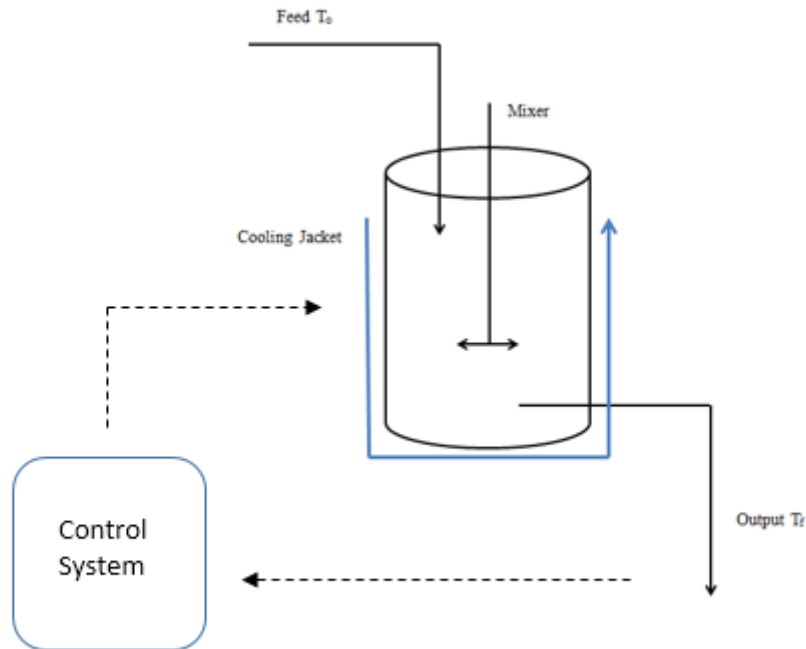
Figure 4: CSTR with control system that measures the output temperature to apply a change to the cooling jacket temperature

One of the most common and simple control techniques is proportional-integral-derivative (PID) control. In this control scheme, the system measures the output temperature and subtracts the desired temperature (in our case the middle-steady state temperature) from the output temperature to find the error in temperature. The error corresponds to the following equation:

$$E(t) = T_{desired} - T_{output}$$

The error is simply the difference in temperature that indicates how far the temperature is from the desired value. The error is time-dependent, meaning that the difference between the desired temperature and output temperature will change with time. The graph below presents how the error changes with time and how it relates to the desired and output temperature:
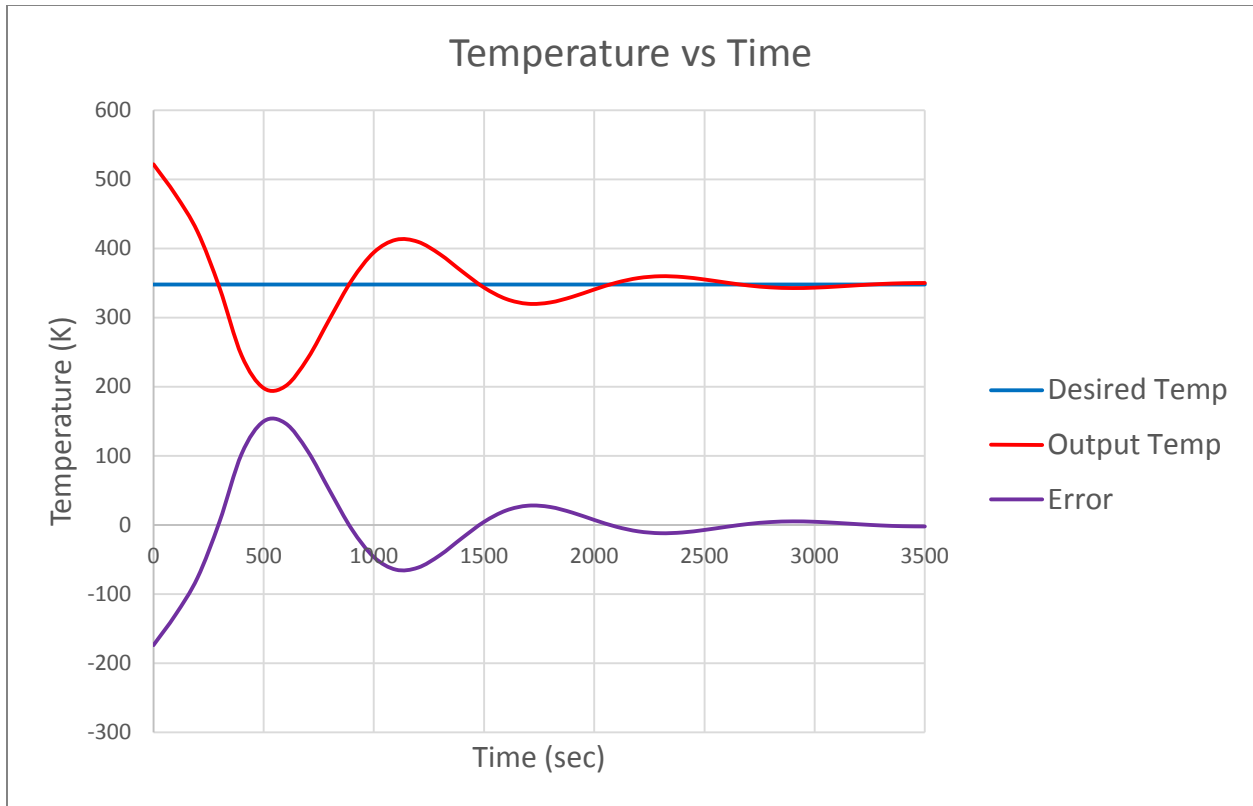
Figure 5: The relationship between the desired temperature, the output temperature, and the error

The error is then incorporated into three separate terms: the proportional term, the integral term, and the derivative term as shown below:

$$Q(t) = Q_o \left[K_P\, E(t) + K_I \int_0^t E(t)dt + K_D\, \frac{dE(t)}{dt} \right]$$

In this equation, $Q(t)$ is the heat added to the cooling water or removed from the cooling water at any moment in time. The temperature of the cooling water affects the heat removed from the system (a lower cooling water temperature results in a greater amount of heat removed). Q_o is simply a constant that indicates a standard amount of heat that will be added or removed from the cooling water.

The three terms within the brackets of the above equation have significance for this assignment. The three terms can be seen visually with the following graph:

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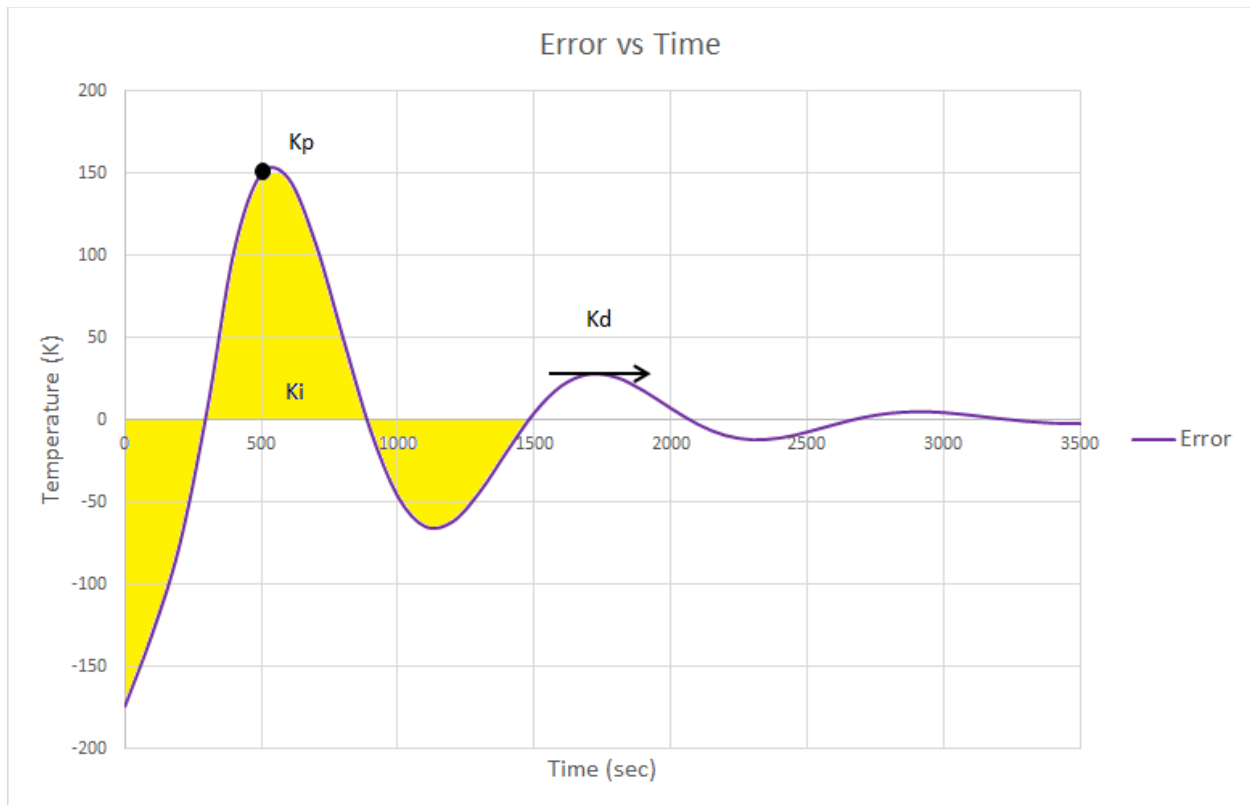
Figure 6: The function of each term in PID control

The term, $K_P E(t)$ is the proportional term. This term takes error at each moment in time and multiplies the error by the value K_P. The magnitude of K_P determines the weight that the error has in PID control. For instance, in Figure 6 at 500 seconds the difference between the desired temperature and the instantaneous temperature is 150 K. If K_P is set to a value of 1, then the control system will add 150 J of heat to the system. If K_P is set to a value of 3, then the control system will add 450 J of energy to the system. If K_P is too high then a small instantaneous error can result in a large heat output and the temperature will exceed the desired value. If K_P is too low then a large instantaneous error may result in a low heat output and the temperature will not significantly change. It is desired to find a value for K_P that results in a reasonable heat output for any instantaneous error in temperature.

$K_I \int_0^t E(t)dt$ is the integral term. This term takes the integral of the error from the initial point in time to the instantaneous point in time and multiplies this integral by the value K_I. This term accounts for all of the past errors from the start of the reaction to the instantaneous point in time. Like K_P, the magnitude of K_I determines the weight of the term in control. Consider the time of 1500 seconds in Figure 6. The integral from the initial time to 1500 seconds is 70 K*sec. If K_I is set to a value of 1, then the control system will add 70 J of energy to the system. If K_I is set to a value of 0.1, then the control system will add a value of 7 J of energy to the system. The value for K_I should be set to a value that results in a reasonable heat output for the integral time for any temperature.

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$K_D \frac{dE(t)}{dt}$ is the derivative term. This term takes the derivative of the error and multiples the derivative by the value K_D. If the derivative of the error is positive that signifies that the temperature is decreasing, as seen from Figure 5. If the error is positive then the derivative term will provide a positive heat output an attempt to increase the temperature. The derivative term results in a heat output according to the future error and is capable of eliminating large amounts of curvature in a plot. Consider the time of 1700 seconds in Figure 6. At this point in time the derivative is zero. Regardless of the value of K_D, the heat output will be zero at this time since K_D is multiplied by the derivative.

It should be noted that all of these terms operate independently to change the temperature. For instance, if the integral of the error from the initial point in time to the instantaneous point is negative, then the $K_I \int_0^t E(t)dt$ term will try to increase the temperature, even if the current temperature is above the set point. The independent heat output of these three terms will be captured in this assignment to present how each of the three terms react to the temperature differently.

Assignment

First, click the folder icon, enter ATC481X, enter Windows (C:) and then enter the folder: CHE3301ExtraCredit. The contents can be seen in Figure 1 below. Open the files "Simulation.sxl" and "Sonification.maxpat." For "Simulation.sxl," Matlab will be opened, shortly followed by a Simulink window containing a model as shown in Figure 2 below. The "Sonification.maxpat" file will open a window prompting to continue a demo, and the "Demo" button should be selected. After this, the window will close and it will take possibly several minutes for the file to open. You may proceed with the Simulink simulation, as described below while waiting for the "Sonificatuion.maxpat" file to open.
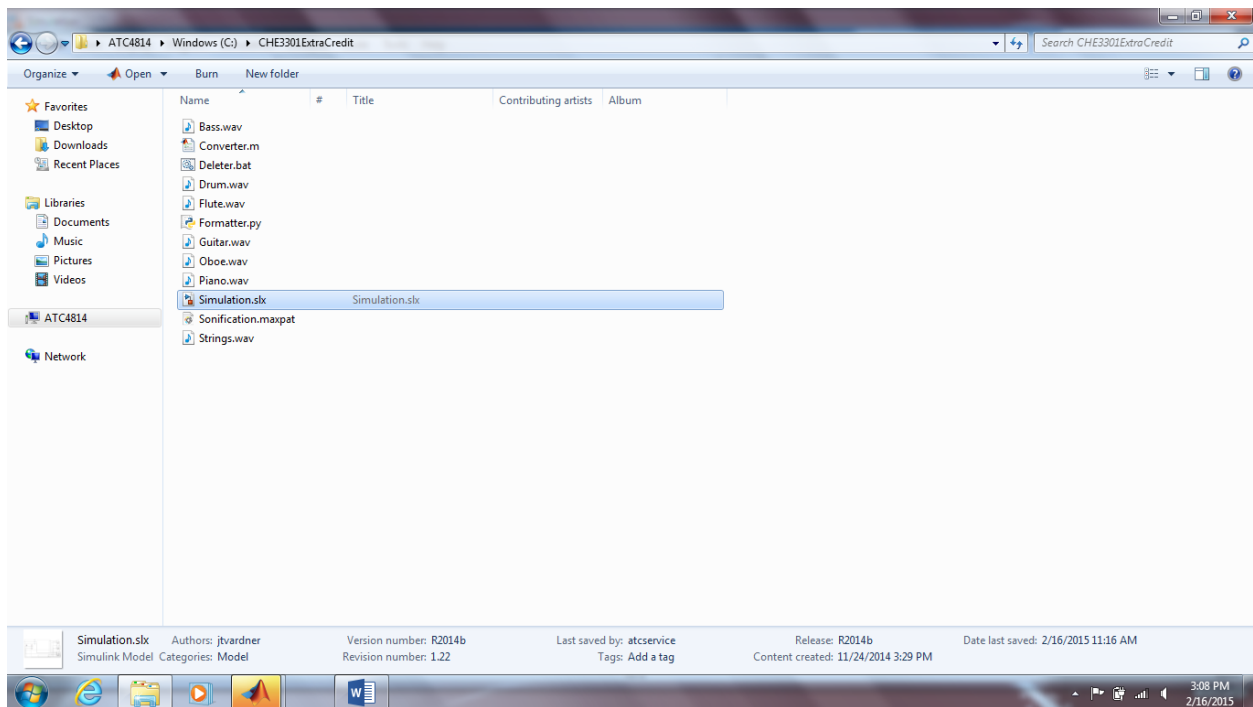
Figure 1: CHE3301ExtraCredit Folder
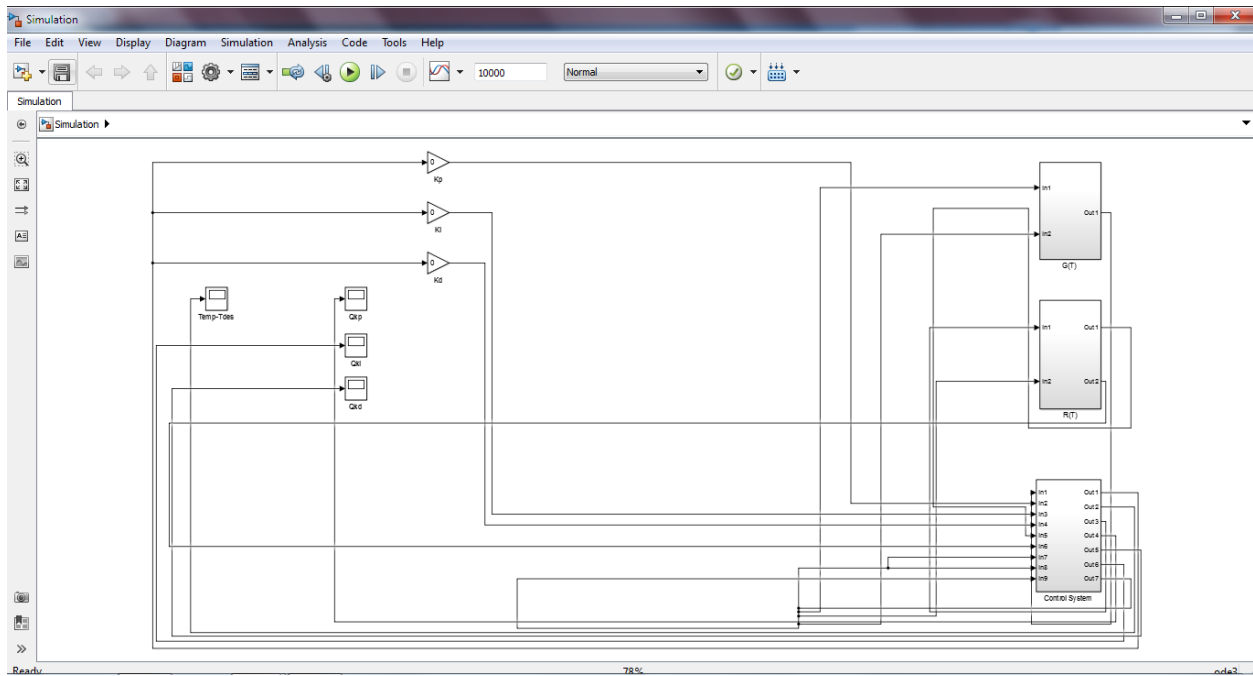
Figure 2: Simulink Model

The right side of the Simulink model consists of the heat gained from the reaction, the heat removed by the cooling water, and the control system to change the cooling water temperature. The left side of the Simulink model consists of the K_P, K_I, and K_D parameters and blocks to display values graphically, as shown in Figure 3 below.
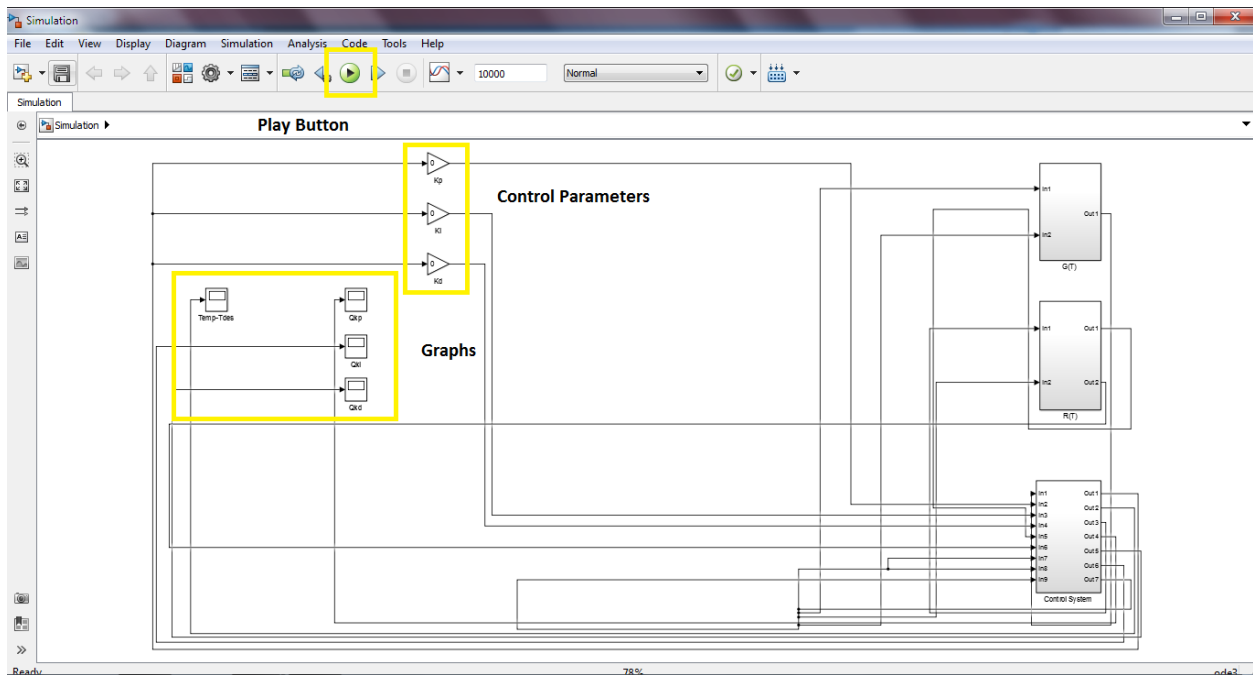
Figure 3: Location of Control Parameters and Graphs

The purpose of this assignment is to change the K_P, K_I, and K_D parameters to converge the temperature from the upper steady state condition to the middle steady state condition. You will be guided through the *Riggs Tuning Method* to achieve this. The K_P, K_I, and K_D parameters are currently set to zero. Run the file pressing the play button (shown in Figure 3).

You can see the temperature and heat outputs graphically by double clicking the graph buttons (shown in figure 3). The *Temp-Tdes* graph presents the middle steady state temperature subtracted from the actual temperature versus time. The difference in temperature demonstrates the displacement of the temperature from its middle steady state condition. The difference is desired to be zero. When the difference is zero the temperature equals the middle steady state temperature. When the difference is positive, the temperature is above the middle steady state condition, and when the difference is negative then the temperature is below the middle steady state condition. The QK_P graph presents the heat output from the $K_P E(t)$ term versus time. The QK_I graph presents the heat output of the $K_I \int_0^t E(t)dt$ term versus time. Lastly, the QK_D graph presents a graph of the heat output of the $K_D \frac{dE(t)}{dt}$ term versus time. Double click the graph that says Temp-Tdes. You should see a graph as in Figure 4 below. You may need to press the autoscale button, also shown in figure 4.

Figure 4. Temp-Tdes Temperature vs Time Graph with No Control System

Notice that the temperature does not deviate from the upper steady state condition. This makes sense considering that the control parameters are set to zero. Thus, there is no heat output driving the system to the middle steady state condition.

After the simulation run in the Simulink model has been completed, go to the Matlab workspace window, which should have automatically been opened on starting up Simulink. In this window, in the bottom left corner under the "Workspace" heading, you should notice that several variables have been created, as seen in Figure 5 below.
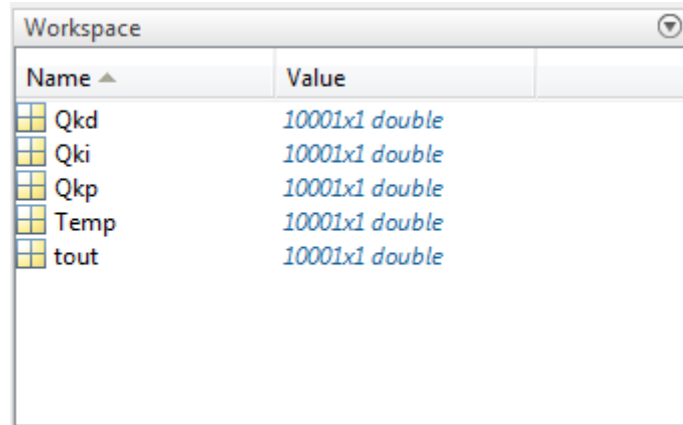
Figure 5. Matlab Workspace Variables

These variables represent the data that was generated as a result of the Simulink simulation run. If these variables are not present, then there was an error in producing the correct output data, and the Simulink simulation should be run again.

In the Matlab workspace window, in the top left corner under the "Current Folder" heading, a file called "Converter.m" should be present, as seen in Figure 6 below.

Figure 6. Matlab Converter Script

This is a Matlab script that is meant to correctly convert the Simulink data into the right form and output it into a .txt file. Simply enter the word "Converter" into the Matlab command prompt like in Figure 7 below and hit enter, and the file should be properly created.
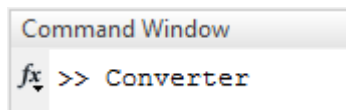
Figure 7. Matlab Command Prompt

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Verify this by searching through the "CHE3301ExtraCredit" folder in order to find the file named "raw_data.txt." If this is present, the conversion was done correctly; otherwise, attempt the conversion again.

In the same "CHE3301ExtraCredit" folder, open the file "Formatter.py." This is a simple script that will properly format the data in "raw_data.txt" into a usable form. When opened, it will briefly open and then close a black terminal window and put the formatted data into new files called "formatted_data.txt," "T_data.txt," "P_data.txt," "I_data.txt," and "D_data.txt." These files will then be accessible by "Sonification.maxpat" for the rest of the assignment.

Navigate to the "Sonification.maxpat" window in MAX, a sonification program to convert data streams to sound. If you have already attempted to open the file and it has not opened yet, please be patient.   It is important to note that MAX may take quite some time to load on a Windows computer. For the patch to load properly and serve its purpose, it is important to wait patiently without restarting or tampering with the loading process. This may take up to several minutes.

When "Sonification.maxpat" is open and responsive, you must simply check that the speaker icon in the bottom right corner of the patch, as shown in Figure 8 below, has been clicked on, select the data you would like to hear from the drop-down menu centered near the top, press the "Read New Data" button, and press the square button in the upper left corner.
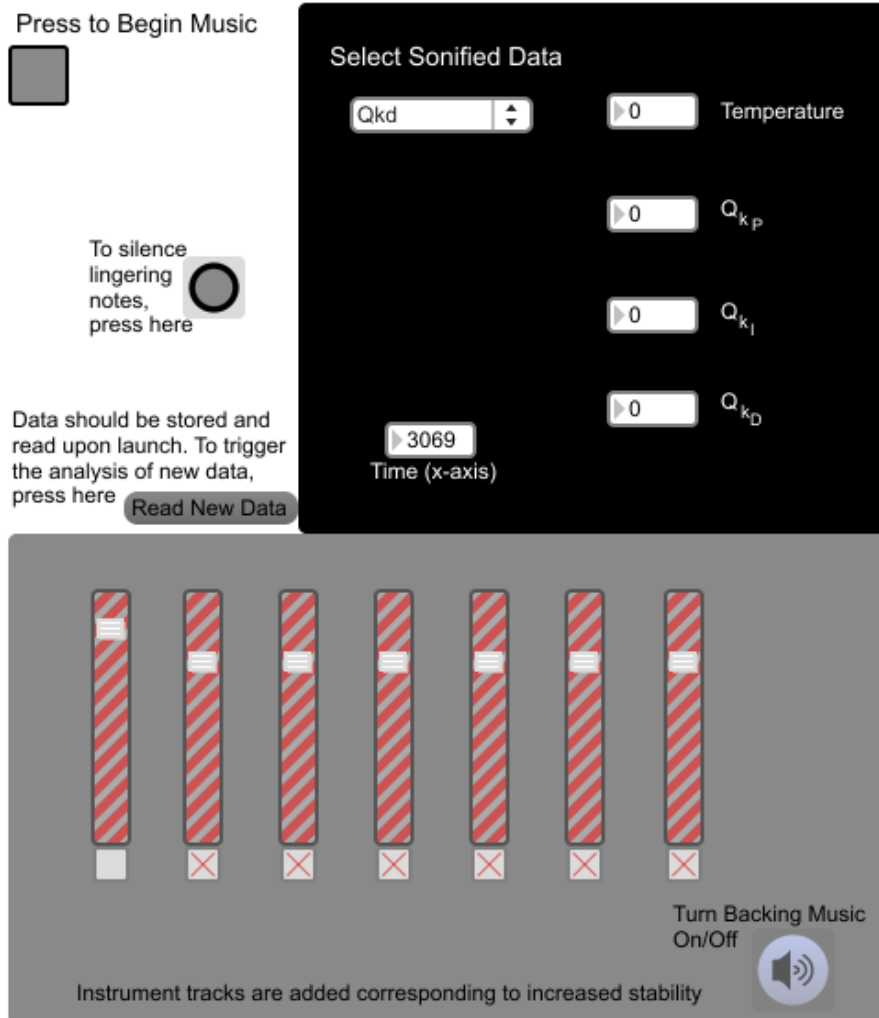
Figure 8. Sonifying MAX Patch

From there, the data will play in its entirety unless stopped by the user. The pitch being played as a trumpet over time is representative of the y-value on the graph. When a C note is played, this is indicative of the y-value being equal to zero. When the value is higher than zero, a note higher than this C is played, and when the value is lower than zero, a note lower than this C is played. The value being represented through this trumpet pitch may be either the temperature or any of the three PID heat values.

To sonify a different collection of data (i.e. temperature, Q_{kD}, etc.) simply press the square button to stop the music, then change your selection in the drop-box. Each time you press the square button, the music restarts from the initial measures and data points.

The background instruments represent the stability of the system. As the temperature value gets closer to zero, more background instruments will be played, until all instruments are being played at exactly a temperature value of zero. As the temperature value gets farther away from

zero, fewer instruments will be played. Regardless of which of the four options is selected from the drop-down box, the background instruments will always be representative of the temperature.

This application is designed to be highly automated for the user, to assure that whatever data collected from Simulink is applied properly. However, the application loads saved data automatically upon loading. If MAX is left open and another simulation is performed in Simulink, the data files will be overwritten but MAX will be using outdated numbers. If you would like to load newly-saved data generated from Simulink without closing and reopening MAX (and risking the long loading time), press the button labelled "Read New Data," which replaces the information stored within MAX with whatever data is properly saved in the same folder.

A summary to convert the data from Simulink to MAX for future parameter sections is shown below:

1. Go to the Matlab command window and type "Converter"
2. Go to the CHE3301ExtraCredit folder and clock Formatter.py
3. Go to MAX and click "Read New Data"
4. Select to sonify Temperature or a parameter heat output and begin the music.

Return to Simulink and set the K_P parameter to 40. To do this double click on the K_P control parameter block (shown in figure 3) and enter the number 40. This will add P-control to the system. The control system will measure the output temperature of the CSTR and then will change the temperature of the cooling water depending on the value that you input for K_P. Click the play button again on Simulink, open the Temp-Tdes graph, perform all necessary conversions of the data files, and play the audio on MAX.

With the K_P value set to 40, the system oscillates between its upper steady state condition and lower steady state condition. Remember that these two steady states are stable. Why is the system having so much trouble converging to its middle steady state?

Increase the K_P value while keeping the K_I and K_D values set to zero, while performing all necessary converting and formatting in order to also sonify the data in MAX. What happens to Temp-Tdes as you increase K_P? What happens to the heat output from the K_P parameter? At what points in time is the K_P heat out put the highest? What is the Temp-Tdes at these points in time? Find a value for K_P that converges Temp-Tdes to zero relatively quickly.

Utilizing the *Riggs Tuning method*, decrease this value of K_P by 10% and input this reduced value for K_P. Then incorporate K_I; start with a value of 0.01 for K_I and observe the temperature response as well as the QK_I heat output visually and audibly.

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Gradually increase the value for K_I. Note that K_I will not greatly improve the temperature response for this system. This is partly because the largest portion of the integral takes place in the first 1200 seconds. How does the value for K_I affects the magnitude of the QK_I heat output? Remember that the QK_I heat output is related to the integral of the error in temperature. What happens to the QK_I heat output over time? How is this related to the integral of the error in temperature over time?

Lastly, tune the K_D parameter. This parameter is particularly useful to eliminate curvature in the Temp-Tdes plot. Start by setting the K_D value to 100. Observe the temperature response as well as the QK_D heat output response both visually and audibly for each parameter that you set.

Since K_D is related to the derivative, it is particularly useful to smooth curvature. What happens to Temp-Tdes as you increase K_D?   What happened to QK_D over time? Why does QK_D have large spikes of heat output and where do these spikes occur?   Increase the value for K_D until you find a set of parameters that tune the system reasonably well.

Lastly, take the post-survey on the next two pages:

Post Survey

Please enter your results for K_P, K_I, and K_D

K_P:
K_I:
K_D:

Please enter your VARK Preliminary Survey Scores next to each learning mode

Visual:
Aural:
Read/Write:
Kinesthetic:

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")

1. I consider myself to be an auditory learner.

        1   2   3   4   5

2. I consider myself to be a visual learner.

        1   2   3   4   5

3. I found the instructions for the assignment to be clear

        1   2   3   4   5

4. I found the software to be simple to use.

        1   2   3   4   5

5. Before using this software, I had an understanding of PID Control.

        1   2   3   4   5

6. After using this software, I feel that my understanding of PID Control improved.

        1   2   3   4   5

7. Before using this software, I had an understanding of Multiple Steady States.

1	2	3	4	5

8. After using this software, I feel that my understanding of Multiple Steady States improved.

1	2	3	4	5

9. I found the auditory component of the assignment to be helpful in conveying the information presented.

1	2	3	4	5

10. I found the visual component of the assignment to be helpful in conveying the information presented.

1	2	3	4	5

11. I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.

1	2	3	4	5

Please answer the following questions in the space provided below:

1. What aspects of the assignment, if any, did you find the most beneficial?

2. What aspects of the assignment, if any, did you find the least beneficial?

3. How would you improve this assignment in any way?

4. Additional comments?

Appendix E: Survey Responses

Student 1

Please enter your results for KP, KI, and KD
KP: 70
KI: 0.015
KD: 125

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 8
Aural: 9
Read/Write: 7
Kinesthetic: 3

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")

1.   I consider myself to be an auditory learner.
                  1   2   3   **4**   5
2.   I consider myself to be a visual learner.
                  1   2   3   **4**   5
3.   I found the instructions for the assignment to be clear
                  1   2   3   **4**   5
4.   I found the software to be simple to use.
                  1   2   **3**   4   5
5.   Before using this software, I had an understanding of PID Control.
                  1   2   3   4   5
6.   After using this software, I feel that my understanding of PID Control improved.
                  1   2   3   **4**   5
7.   Before using this software, I had an understanding of Multiple Steady States.
                  1   2   3   4   5
8.   After using this software, I feel that my understanding of Multiple Steady States improved.
                  1   2   **3**   4   5
9.   I found the auditory component of the assignment to be helpful in conveying the information presented.
                  1   **2**   3   4   5
10.   I found the visual component of the assignment to be helpful in conveying the information presented.
                  1   2   3   4   **5**
11.   I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.
                  1   **2**   3   4   5

Please answer the following questions in the space provided below:

1. What aspects of the assignment, if any, did you find the most beneficial?

Visual input seemed more helpful then auditory, I am used to looking at graphs and analyzing what should be done. Your background info was very helpful and informative!

2. What aspects of the assignment, if any, did you find the least beneficial?

Having to convert things over made me less inclined to listen to the audio, I understand that probably cannot be fixed though

3. How would you improve this assignment in any way?

I think the audio should play slower or have a slowdown button, most of the "action" happens in a short amount of time. It was playing too quickly for me to determine if things changed. Visually on the graph, it is easy to zoom in on a small part of it.

4. Additional comments?

The visual aspects dominated the auditory input. I feel this experiment would have been more useful if we only had auditory input. When I was listening to the audio, I was more trying to compare it to the visual than trying to pick out any nuisances.

Student 2

Please enter your results for KP, KI, and KD
KP: 90
KI: 0.001
KD: 400

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 9
Aural: 6
Read/Write: 8
Kinesthetic: 8

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")

1. I consider myself to be an auditory learner.
    1   2   3   4   5
2. I consider myself to be a visual learner.
    1   2   3   4   5
3. I found the instructions for the assignment to be clear
    1   2   3   4   5
4. I found the software to be simple to use.
    1   2   3   4   5
5. Before using this software, I had an understanding of PID Control.
    1   2   3   4   5
6. After using this software, I feel that my understanding of PID Control improved.
    1   2   3   4   5
7. Before using this software, I had an understanding of Multiple Steady States.
    1   2   3   4   5
8. After using this software, I feel that my understanding of Multiple Steady States improved.
    1   2   3   4   5
9. I found the auditory component of the assignment to be helpful in conveying the information presented.
    1   2   3   4   5
10. I found the visual component of the assignment to be helpful in conveying the information presented.
    1   2   3   4   5
11. I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.
    1   2   3   4   5

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Please answer the following questions in the space provided below:

1.   What aspects of the assignment, if any, did you find the most beneficial?

Being able to change the control parameters and almost instantly be able to see the change in the Temp-Tdes graph was very helpful in seeing the effect of each parameter.

2.   What aspects of the assignment, if any, did you find the least beneficial?

While using MAX at first was interesting, I found it to be too inefficient to use the sound to see the trend. It is a good method to observing just the trend, but I prefer to see the numbers at which the peaks and other information occur (which is easiest on the graph).

3.   How would you improve this assignment in any way?

Add screenshots from the initial control parameters. I wasn't sure at first if everything was working as it should, and I am not fully convinced I got MAX working as it should (Q_{kd} and Q_{ki} values didn't mimic the trend shown in the Matlab graph—although this was probably my fault).

4.   Additional comments?

I now know I am, without a doubt, a visual learner. Although the auditory method was definitely interesting and I can easily see how other people would find that method more beneficial.

Student 3

Please enter your results for KP, KI, and KD
KP: 90
KI: 0.45
KD: 130

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 5
Aural: 7
Read/Write: 8
Kinesthetic: 3

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")
1.   I consider myself to be an auditory learner.
                        1   2   3   4   5
2.   I consider myself to be a visual learner.
                        1   2   3   4   5
3.   I found the instructions for the assignment to be clear
                        1   2   3   4   5
4.   I found the software to be simple to use.
                        1   2   3   4   5
5.   Before using this software, I had an understanding of PID Control.
                        1   2   3   4   5
6.   After using this software, I feel that my understanding of PID Control improved.
                        1   2   3   4   5
7.   Before using this software, I had an understanding of Multiple Steady States.
                        1   2   3   4   5
8.   After using this software, I feel that my understanding of Multiple Steady States improved.
                        1   2   3   4   5
9.   I found the auditory component of the assignment to be helpful in conveying the information presented.
                        1   2   3   4   5
10.   I found the visual component of the assignment to be helpful in conveying the information presented.
                        1   2   3   4   5
11.   I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.
                        1   2   3   4   5

Please answer the following questions in the space provided below:

1.　　　What aspects of the assignment, if any, did you find the most beneficial?

The temp tides graph helped me the most

2.　　　What aspects of the assignment, if any, did you find the least beneficial?

The max software at some points was very unpleasant sounding

3.　　　How would you improve this assignment in any way?

List sample values for the variables that can help steer people in the right direction. Create a Ctrl+Alt key that can automate the intermediate steps of formatting and converting the data

4.　　　Additional comments?

Student 4

Please enter your results for KP, KI, and KD
KP: 90
KI: 0.03
KD: 500

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 11
Aural: 8
Read/Write: 4
Kinesthetic: 5

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")

1.   I consider myself to be an auditory learner.
        1   2   3   4   5
2.   I consider myself to be a visual learner.
        1   2   3   4   5
3.   I found the instructions for the assignment to be clear
        1   2   3   4   5
4.   I found the software to be simple to use.
        1   2   3   4   5
5.   Before using this software, I had an understanding of PID Control.
        1   2   3   4   5
6.   After using this software, I feel that my understanding of PID Control improved.
        1   2   3   4   5
7.   Before using this software, I had an understanding of Multiple Steady States.
        1   2   3   4   5
8.   After using this software, I feel that my understanding of Multiple Steady States improved.
        1   2   3   4   5
9.   I found the auditory component of the assignment to be helpful in conveying the information presented.
        1   2   3   4   5
10.   I found the visual component of the assignment to be helpful in conveying the information presented.
        1   2   3   4   5
11.   I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.
        1   2   3   4   5

Please answer the following questions in the space provided below:

1.   What aspects of the assignment, if any, did you find the most beneficial?

I found that I learned the most from the graphs of temperature, Qkp, Qki and Qkd. The auditory component was helpful at first, however, I stopped using it after a while because I found the music to be distracting.

2.   What aspects of the assignment, if any, did you find the least beneficial?

N/A

3.   How would you improve this assignment in any way?

I think having an instructor do it on a projector would be easier because I the instructions were a little overwhelming near the end. And then let the students play with it and figure out the numbers at the end.

4.   Additional comments?

I think this is very interesting and you all did a great job!

Student 5

Please enter your results for KP, KI, and KD
KP: 33
KI: 0.03
KD: 425

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 9
Aural: 7
Read/Write: 7
Kinesthetic: 9

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")

1. I consider myself to be an auditory learner.
    1   2   3   4   **5**

2. I consider myself to be a visual learner.
    1   2   3   4   **5**

3. I found the instructions for the assignment to be clear
    1   2   3   **4**   5

4. I found the software to be simple to use.
    1   2   3   4   **5**

5. Before using this software, I had an understanding of PID Control.
    1   **2**   3   4   5

6. After using this software, I feel that my understanding of PID Control improved.
    1   2   3   **4**   5

7. Before using this software, I had an understanding of Multiple Steady States.
    1   **2**   3   4   5

8. After using this software, I feel that my understanding of Multiple Steady States improved.
    1   2   3   4   **5**

9. I found the auditory component of the assignment to be helpful in conveying the information presented.
    1   2   3   4   **5**

10. I found the visual component of the assignment to be helpful in conveying the information presented.
    1   2   3   4   **5**

11. I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.
    1   2   3   4   **5**

Please answer the following questions in the space provided below:

1.   What aspects of the assignment, if any, did you find the most beneficial?
I thought the pictures were very beneficial to ensure that I was doing things correctly!

2.   What aspects of the assignment, if any, did you find the least beneficial?
The wording was a bit confusing at time so I had to reread some of the instruction more than once but overall it was fine.

3.   How would you improve this assignment in any way?
Maybe changing the wording a bit.

4.   Additional comments?
Overall I thought it is a very interesting project! Great Job!

Student 6

Please enter your results for KP, KI, and KD
KP: 100
KI: 0.01
KD: 550

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 8
Aural: 6
Read/Write: 12
Kinesthetic: 5

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")

1. I consider myself to be an auditory learner.

    1 2 3 4 5

2. I consider myself to be a visual learner.

    1 2 3 4 5

3. I found the instructions for the assignment to be clear

    1 2 3 4 5

4. I found the software to be simple to use.

    1 2 3 4 5

5. Before using this software, I had an understanding of PID Control.

    1 2 3 4 5

6. After using this software, I feel that my understanding of PID Control improved.

    1 2 3 4 5

7. Before using this software, I had an understanding of Multiple Steady States.

    1 2 3 4 5

8. After using this software, I feel that my understanding of Multiple Steady States improved.

    1 2 3 4 5

9. I found the auditory component of the assignment to be helpful in conveying the information presented.

    1 2 3 4 5

10. I found the visual component of the assignment to be helpful in conveying the information presented.

    1 2 3 4 5

11. I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.

    1 2 3 4 5

Please answer the following questions in the space provided below:

1.   What aspects of the assignment, if any, did you find the most beneficial?

I found the most beneficial aspect of this assignment to be the visuals in the directions and the exercise. I had a much better understanding of what was going on from them. Also I really enjoyed taking the learning test beforehand and then doing the assignment because I got to see how I had a better understanding of visuals then audio, just like the results of the learning test showed me.

2.   What aspects of the assignment, if any, did you find the least beneficial?

I found the assignment beneficial overall.

3.   How would you improve this assignment in any way?

I would improve this assignment by clairifying if the final results of Kp, KI, and Kd are to get the temperature to be the steadiest or each individual parameter and the temperature to be the steadiest. Also When it is stated that KI is the integral of the error in temperature I was a bit confused.

4.   Additional comments?

You guys have a really awesome IQP project! Nice job :) Good luck with everything.

Student 7

Please enter your results for KP, KI, and KD
KP: 73
KI: 0.05
KD: 1000

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 9
Aural: 6
Read/Write: 7
Kinesthetic: 12

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")

1.　　I consider myself to be an auditory learner.
　　　　　　1　　　　　2　　　　　3　　　　　**4**　　　　　5
2.　　I consider myself to be a visual learner.
　　　　　　1　　　　　2　　　　　**3**　　　　　4　　　　　5
3.　　I found the instructions for the assignment to be clear
　　　　　　1　　　　　2　　　　　3　　　　　4　　　　　5
4.　　I found the software to be simple to use.
　　　　　　1　　　　　2　　　　　**3**　　　　　4　　　　　5
5.　　Before using this software, I had an understanding of PID Control.
　　　　　　1　　　　　2　　　　　3　　　　　4　　　　　**5**
6.　　After using this software, I feel that my understanding of PID Control improved.
　　　　　　1　　　　　2　　　　　**3**　　　　　4　　　　　5
7.　　Before using this software, I had an understanding of Multiple Steady States.
　　　　　　1　　　　　2　　　　　**3**　　　　　4　　　　　5
8.　　After using this software, I feel that my understanding of Multiple Steady States improved.
　　　　　　1　　　　　2　　　　　3　　　　　**4**　　　　　5
9.　　I found the auditory component of the assignment to be helpful in conveying the information presented.
　　　　　　1　　　　　2　　　　　3　　　　　**4**　　　　　5
10.　　I found the visual component of the assignment to be helpful in conveying the information presented.
　　　　　　1　　　　　2　　　　　**3**　　　　　4　　　　　5
11.　　I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.
　　　　　　1　　　　　2　　　　　3　　　　　4　　　　　**5**

Please answer the following questions in the space provided below:

1.   What aspects of the assignment, if any, did you find the most beneficial?
Listening to the trumpet while looking at the graph was entertaining and informative to the tuning process.

2.   What aspects of the assignment, if any, did you find the least beneficial?
The instructions…

3.   How would you improve this assignment in any way?
Clearer instructions. The hardest part was figuring out how to open files and work the program.

4.   Additional comments?
Cool project!

Student 8

Please enter your results for KP, KI, and KD
KP: 54
KI: 0.01
KD: 300

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 9
Aural: 6
Read/Write: 8
Kinesthetic: 7

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")

1.   I consider myself to be an auditory learner.
          1   2   3   4   5

2.   I consider myself to be a visual learner.
          1   2   3   4   5

3.   I found the instructions for the assignment to be clear
          1   2   3   4   5

4.   I found the software to be simple to use.
          1   2   3   4   5

5.   Before using this software, I had an understanding of PID Control.
          1   2   3   4   5

6.   After using this software, I feel that my understanding of PID Control improved.
          1   2   3   4   5

7.   Before using this software, I had an understanding of Multiple Steady States.
          1   2   3   4   5

8.   After using this software, I feel that my understanding of Multiple Steady States improved.
          1   2   3   4   5

9.   I found the auditory component of the assignment to be helpful in conveying the information presented.
          1   2   3   4   5

10.   I found the visual component of the assignment to be helpful in conveying the information presented.
          1   2   3   4   5

11.   I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.
          1   2   3   4   5

Please answer the following questions in the space provided below:

1.   What aspects of the assignment, if any, did you find the most beneficial?

I found it beneficial to see the effects of changing the parameters on the system's response in the graphs.

2.   What aspects of the assignment, if any, did you find the least beneficial?

3.   How would you improve this assignment in any way?

Make this assignment accessible via VPN.

4.   Additional comments?

Student 9

Please enter your results for KP, KI, and KD
KP: 81
KI: 0.01
KD: 550

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 9
Aural: 4
Read/Write: 9
Kinesthetic: 10

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")
1.   I consider myself to be an auditory learner.
                        1   2   3   4   5
2.   I consider myself to be a visual learner.
                        1   2   3   4   5
3.   I found the instructions for the assignment to be clear
                        1   2   3   4   5
4.   I found the software to be simple to use.
                        1   2   3   4   5
5.   Before using this software, I had an understanding of PID Control.
                        1   2   3   4   5
6.   After using this software, I feel that my understanding of PID Control improved.
                        1   2   3   4   5
7.   Before using this software, I had an understanding of Multiple Steady States.
                        1   2   3   4   5
8.   After using this software, I feel that my understanding of Multiple Steady States improved.
                        1   2   3   4   5
9.   I found the auditory component of the assignment to be helpful in conveying the information presented.
                        1   2   3   4   5
10.   I found the visual component of the assignment to be helpful in conveying the information presented.
                        1   2   3   4   5
11.   I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.
                        1   2   3   4   5

Please answer the following questions in the space provided below:

1.   What aspects of the assignment, if any, did you find the most beneficial?

The auditory stuff was cool but the novelty of it quickly wore off for me, honestly I liked changing the parameters and seeing the effects it had on the graph, very similar to comsol runs done in UO1.

2.   What aspects of the assignment, if any, did you find the least beneficial?

Probably the auditory stuff, though I enjoyed it when the KP value was jacked up high and the others were set to zero. It made it oscillate a lot and created a cool sound effect.

3.   How would you improve this assignment in any way?

Make it easier to play the audio, make it more automatic formatting, it was a deterrent to play it during the tuning procedure for someone who would rather look at the graphs anyway.

4.   Additional comments?

This is a very interesting concept and I'm very interested in seeing the results and possibly where other applications are, especially for those who are auditory learners unlike myself.

Student 10

Please enter your results for KP, KI, and KD
KP: 90
KI: 0.04
KD: 280

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 9
Aural: 11
Read/Write: 9
Kinesthetic: 14

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")

1. I consider myself to be an auditory learner.
   1   2   3   4   5
2. I consider myself to be a visual learner.
   1   2   3   4   5
3. I found the instructions for the assignment to be clear
   1   2   3   4   5
4. I found the software to be simple to use.
   1   2   3   4   5
5. Before using this software, I had an understanding of PID Control.
   1   2   3   4   5
6. After using this software, I feel that my understanding of PID Control improved.
   1   2   3   4   5
7. Before using this software, I had an understanding of Multiple Steady States.
   1   2   3   4   5
8. After using this software, I feel that my understanding of Multiple Steady States improved.
   1   2   3   4   5
9. I found the auditory component of the assignment to be helpful in conveying the information presented.
   1   2   3   4   5
10. I found the visual component of the assignment to be helpful in conveying the information presented.
   1   2   3   4   5
11. I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.
   1   2   3   4   5

Please answer the following questions in the space provided below:

1.   What aspects of the assignment, if any, did you find the most beneficial?
The background information was very useful. The graphs were useful as well.

2.   What aspects of the assignment, if any, did you find the least beneficial?
All of it was useful, but if I had to choose one thing it would be the audio representation.

3.   How would you improve this assignment in any way?
I think that everything was extremely well-explained.

4.   Additional comments?
Good luck on the report!

Student 11

Please enter your results for KP, KI, and KD
KP: 150
KI: 0.1
KD: 100

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 6
Aural: 7
Read/Write: 8
Kinesthetic: 7

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")

1.   I consider myself to be an auditory learner.
                  1   2   3   4   5

2.   I consider myself to be a visual learner.
   1   2   3   4   **5**
- 1:   2:   3:   4:   5: **highlighted**

3.   I found the instructions for the assignment to be clear
- 1:   2: **highlighted**   3:   4:   5:

4.   I found the software to be simple to use.
- 1:   2: **highlighted**   3:   4:   5:

5.   Before using this software, I had an understanding of PID Control.
- 1:   2:   3:   4: **highlighted**   5:

6.   After using this software, I feel that my understanding of PID Control improved.
- 1:   2:   3:   4: **highlighted**   5:

7.   Before using this software, I had an understanding of Multiple Steady States.
- 1: **highlighted**   2:   3:   4:   5:

8.   After using this software, I feel that my understanding of Multiple Steady States improved.
- 1:   2:   3:   4: **highlighted**   5:

9.   I found the auditory component of the assignment to be helpful in conveying the information presented.
- 1: **highlighted**   2:   3:   4:   5:

10.   I found the visual component of the assignment to be helpful in conveying the information presented.
- 1:   2:   3:   4: **highlighted**   5:

11.   I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.
- 1: **highlighted**   2:   3:   4:   5:

Please answer the following questions in the space provided below:

1.   What aspects of the assignment, if any, did you find the most beneficial?
The background reading was useful, it helped me to understand what I am supposed to do.

2.   What aspects of the assignment, if any, did you find the least beneficial?
The sound portion.

3.   How would you improve this assignment in any way?
I would not put instructions in paragraph form…it is very confusing for me. I think lists are easier to follow.

You should have given a demonstration of what "C" sounds like.

I also don't understand how to know which sound from the drop-down I am supposed to listen to.

4.   Additional comments?

Student 12

Please enter your results for KP, KI, and KD
KP: 60
KI: 0.01
KD: 100

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 8
Aural: 8
Read/Write: 6
Kinesthetic: 6

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")

1.   I consider myself to be an auditory learner.
                        1   2   3   4   5
2.   I consider myself to be a visual learner.
                        1   2   3   4   5
3.   I found the instructions for the assignment to be clear
                        1   2   3   4   5
4.   I found the software to be simple to use.
                        1   2   3   4   5
5.   Before using this software, I had an understanding of PID Control.
                        1   2   3   4   5
6.   After using this software, I feel that my understanding of PID Control improved.
                        1   2   3   4   5
7.   Before using this software, I had an understanding of Multiple Steady States.
                        1   2   3   4   5
8.   After using this software, I feel that my understanding of Multiple Steady States improved.
                        1   2   3   4   5
9.   I found the auditory component of the assignment to be helpful in conveying the information presented.
                        1   2   3   4   5
10.   I found the visual component of the assignment to be helpful in conveying the information presented.
                        1   2   3   4   5
11.   I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.
                        1   2   3   4   5

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Please answer the following questions in the space provided below:

1.   What aspects of the assignment, if any, did you find the most beneficial?

I thought the introduction to PID control was very well written and explained

2.   What aspects of the assignment, if any, did you find the least beneficial?

The auditory part. I thought it was cool, but it buzzed in my ear a lot and it sounded bad, probably because I was doing it wrong though.

3.   How would you improve this assignment in any way?

Make it react to matlab as soon as it compiles instead of having to be converted then formatted and then loaded and then played.

4.   Additional comments?

I think this was cool

Student 13

Please enter your results for KP, KI, and KD
KP: 100
KI: 0.01
KD: 350

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 13
Aural: 7
Read/Write: 14
Kinesthetic: 12

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")

1. I consider myself to be an auditory learner.
   1   2   3   4   5

2. I consider myself to be a visual learner.
   1   2   3   4   5

3. I found the instructions for the assignment to be clear
   1   2   3   4   5

4. I found the software to be simple to use.
   1   2   3   4   5

5. Before using this software, I had an understanding of PID Control.
   1   2   3   4   5

6. After using this software, I feel that my understanding of PID Control improved.
   1   2   3   4   5

7. Before using this software, I had an understanding of Multiple Steady States.
   1   2   3   4   5

8. After using this software, I feel that my understanding of Multiple Steady States improved.
   1   2   3   4   5

9. I found the auditory component of the assignment to be helpful in conveying the information presented.
   1   2   3   4   5

10. I found the visual component of the assignment to be helpful in conveying the information presented.
    1   2   3   4   5

11. I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.
    1   2   3   4   5

Highlighted answers:
1. 2
2. 4
3. 3
4. 3
5. 3
6. 2
7. 3
8. 2
9. 1
10. 5
11. 1

Please answer the following questions in the space provided below:

1.	What aspects of the assignment, if any, did you find the most beneficial?
The plots, variables were easy to adjust and plots automatically updated to see effect

2.	What aspects of the assignment, if any, did you find the least beneficial?
Auditory component, hard to play sounds while following the plots
Instruments did not indicate how far off from steady state system was, no magnitude/scale from sounds, number of instruments playing was only an indication of where system was in relation to steady state
Stimulation flowsheet looked neat but the lines were hard to follow, that might not be part of the assignment though

3.	How would you improve this assignment in any way?
Maybe use increasing/decreasing volume of instruments as a way of indicating magnitude of response
Might not be possible but I think it'd help a lot if you could combine the plotting the graph and playing the music simultaneously.

4.	Additional comments?
May be useful to others who have studied music but I found the variety of instruments to be distracting. It was much easier to look at the plots and understand how the system responded than listen to the number of instruments playing

Student 14

Please enter your results for KP, KI, and KD
KP: 32
KI: 0.05
KD: 80

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 7
Aural: 5
Read/Write: 5
Kinesthetic: 5

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")

1.   I consider myself to be an auditory learner.
                    1   2   3   4   5
2.   I consider myself to be a visual learner.
                    1   2   3   4   5
3.   I found the instructions for the assignment to be clear
                    1   2   3   4   5
4.   I found the software to be simple to use.
                    1   2   3   4   5
5.   Before using this software, I had an understanding of PID Control.
                    1   2   3   4   5
6.   After using this software, I feel that my understanding of PID Control improved.
                    1   2   3   4   5
7.   Before using this software, I had an understanding of Multiple Steady States.
                    1   2   3   4   5
8.   After using this software, I feel that my understanding of Multiple Steady States improved.
                    1   2   3   4   5
9.   I found the auditory component of the assignment to be helpful in conveying the information presented.
                    1   2   3   4   5
10.   I found the visual component of the assignment to be helpful in conveying the information presented.
                    1   2   3   4   5
11.   I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.
                    1   2   3   4   5

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Please answer the following questions in the space provided below:
1.   What aspects of the assignment, if any, did you find the most beneficial?
The very detailed background information and the graphs showing the responce

2.   What aspects of the assignment, if any, did you find the least beneficial?
The auditory representation was a little bit tough to get used to

3.   How would you improve this assignment in any way?
If possible make the program more concised and user friendly

4.   Additional comments?

Student 15

Please enter your results for KP, KI, and KD
KP: 80
KI: 0.001
KD: 1000

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 4
Aural: 5
Read/Write: 6
Kinesthetic: 6

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")

1.	I consider myself to be an auditory learner.
1   2   3   4   5

2.	I consider myself to be a visual learner.
1   2   3   4   5

3.	I found the instructions for the assignment to be clear
1   2   3   4   5

4.	I found the software to be simple to use.
1   2   3   4   5

5.	Before using this software, I had an understanding of PID Control.
1   2   3   4   5

6.	After using this software, I feel that my understanding of PID Control improved.
1   2   3   4   5

7.	Before using this software, I had an understanding of Multiple Steady States.
1   2   3   4   5

8.	After using this software, I feel that my understanding of Multiple Steady States improved.
1   2   3   4   5

9.	I found the auditory component of the assignment to be helpful in conveying the information presented.
1   2   3   4   5

10.	I found the visual component of the assignment to be helpful in conveying the information presented.
1   2   3   4   5

11.	I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.
1   2   3   4   5

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Please answer the following questions in the space provided below:
1.   What aspects of the assignment, if any, did you find the most beneficial?
The visual graphs are most beneficial.

2.   What aspects of the assignment, if any, did you find the least beneficial?
The sound tones are not helpful because you must analyze it in real time. With visuals you can see the entire picture and magnitudes of error. At some point in the audio, there is no way to tell how much farther away it is from the steady state.   I have no musical background so there are points where it is hard to tell the differences in sound once they are put together. There isn't a way to tell from the audio if the error is above or below the steady-state.

3.   How would you improve this assignment in any way?

4.   Additional comments?
The sound is harsh on the ears listening to it making it uncomfortable.

Student 16

Please enter your results for KP, KI, and KD
KP: 69
KI: 0.027
KD: 800

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 4
Aural: 1
Read/Write: 2
Kinesthetic: 9

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")

1.   I consider myself to be an auditory learner.
        1   `2`   3   4   5

2.   I consider myself to be a visual learner.
        1   2   `3`   4   5

3.   I found the instructions for the assignment to be clear
        1   2   `3`   4   5

4.   I found the software to be simple to use.
        1   `2`   3   4   5

5.   Before using this software, I had an understanding of PID Control.
        1   2   3   `4`   5

6.   After using this software, I feel that my understanding of PID Control improved.
        1   2   3   `4`   5

7.   Before using this software, I had an understanding of Multiple Steady States.
        1   2   3   `4`   5

8.   After using this software, I feel that my understanding of Multiple Steady States improved.
        1   2   3   `4`   5

9.   I found the auditory component of the assignment to be helpful in conveying the information presented.
        1   `2`   3   4   5

10.   I found the visual component of the assignment to be helpful in conveying the information presented.
        1   2   3   `4`   5

11.   I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.
        1   `2`   3   4   5

Please answer the following questions in the space provided below:

1.	What aspects of the assignment, if any, did you find the most beneficial?
The MatLab graph, I found was, much more helpful than the auditory trumpets.

2.	What aspects of the assignment, if any, did you find the least beneficial?
The musical aspects benefits were lost on me and didn't really help in the long run.

3.	How would you improve this assignment in any way?
Have a step by step tutorial for the Kp Ki and Kd changing aspects of the material.

4.	Additional comments?
N/A

Student 17

Please enter your results for KP, KI, and KD
KP: 105
KI: 0.05
KD: 200

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 9
Aural: 9
Read/Write: 12
Kinesthetic: 10

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")

1.   I consider myself to be an auditory learner.
                    1   2   3   4   5
2.   I consider myself to be a visual learner.
                    1   2   3   4   5
3.   I found the instructions for the assignment to be clear
                    1   2   3   4   5
4.   I found the software to be simple to use.
                    1   2   3   4   5
5.   Before using this software, I had an understanding of PID Control.
                    1   2   3   4   5
6.   After using this software, I feel that my understanding of PID Control improved.
                    1   2   3   4   5
7.   Before using this software, I had an understanding of Multiple Steady States.
                    1   2   3   4   5
8.   After using this software, I feel that my understanding of Multiple Steady States improved.
                    1   2   3   4   5
9.   I found the auditory component of the assignment to be helpful in conveying the information presented.
                    1   2   3   4   5
10.   I found the visual component of the assignment to be helpful in conveying the information presented.
                    1   2   3   4   5
11.   I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.
                    1   2   3   4   5

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Please answer the following questions in the space provided below:

1.   What aspects of the assignment, if any, did you find the most beneficial?

I found the graphical component of this exercise to be the most beneficial, especially representing multiple steady states in the preliminary reading. It allowed me to see the phenomena occurring in a manner I understand that also suited the information being conveyed, primarily a number changing over time and integrals on a graph compared to zero.

2.   What aspects of the assignment, if any, did you find the least beneficial?

Honestly, I found the aural component the least beneficial. While it did give me a more visceral sensation of the temperature oscillations, eventually the oscillations became too quick for the program to register a change in tone which was most present at higher Kd values.

3.   How would you improve this assignment in any way?

I'm not sure if I just wasn't sure what to expect or not, but the background music as a measure of "stability" is somewhat ill-defined. I did notice every now and then that it skipped a bit or sounded extremely sped up but I could not determine what "instability" was causing this since very high Kp values that resulted in uncontrolled oscillation still had uninterrupted play.

4.   Additional comments?

Not at this time. All of my criticism was spent in the previous three questions.

Student 18

Please enter your results for KP, KI, and KD
KP: 75
KI: 0.05
KD: 160

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 7
Aural: 10
Read/Write: 5
Kinesthetic: 11

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")

1.   I consider myself to be an auditory learner.

    1   2   3   4   5

2.   I consider myself to be a visual learner.

    1   2   3   4   5

3.   I found the instructions for the assignment to be clear

    1   2   3   4   5

4.   I found the software to be simple to use.

    1   2   3   4   5

5.   Before using this software, I had an understanding of PID Control.

    1   2   3   4   5

6.   After using this software, I feel that my understanding of PID Control improved.

    1   2   3   4   5

7.   Before using this software, I had an understanding of Multiple Steady States.

    1   2   3   4   5

8.   After using this software, I feel that my understanding of Multiple Steady States improved.

    1   2   3   4   5

9.   I found the auditory component of the assignment to be helpful in conveying the information presented.

    1   2   3   4   5

10.   I found the visual component of the assignment to be helpful in conveying the information presented.

    1   2   3   4   5

11.   I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.

    1   2   3   4   5

Please answer the following questions in the space provided below:

1.   What aspects of the assignment, if any, did you find the most beneficial?

I thought the idea and implementation on the auditory component was helpful in learning the concepts prevented. I feel that this is great in supplement to visual learning.

2.   What aspects of the assignment, if any, did you find the least beneficial?

I found the formatting and converting part a bit confusing, but I understand it was part of the software development stages.

3.   How would you improve this assignment in any way?

Organization of the files could have been a bit better, but this is minor. The assignment was good.

4.   Additional comments?

To reiterate a bit, the dual learning of auditory and visual for this assignment helped re-emphasize and teach the material better, so I believe it is a good implementation and something to be used in engineering courses.

Student 19

Please enter your results for KP, KI, and KD
KP: 60
KI: 0.02
KD: 700

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 8
Aural: 4
Read/Write: 8
Kinesthetic: 9

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")

1. I consider myself to be an auditory learner.
             1   2   3   4   5

2. I consider myself to be a visual learner.
             1   2   3   **4**   5

3. I found the instructions for the assignment to be clear
             1   **2**   3   4   5

4. I found the software to be simple to use.
             1   **2**   3   4   5

5. Before using this software, I had an understanding of PID Control.
             1   2   3   4   **5**

6. After using this software, I feel that my understanding of PID Control improved.
             1   **2**   3   4   5

7. Before using this software, I had an understanding of Multiple Steady States.
             1   2   **3**   4   5

8. After using this software, I feel that my understanding of Multiple Steady States improved.
             1   2   **3**   4   5

9. I found the auditory component of the assignment to be helpful in conveying the information presented.
             1   **2**   3   4   5

10. I found the visual component of the assignment to be helpful in conveying the information presented.
              1   2   3   4   **5**

11. I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.
              1   2   **3**   4   5

Please answer the following questions in the space provided below:

1.   What aspects of the assignment, if any, did you find the most beneficial?

I found the graphs and seeing the outputs and comparing them to the different inputs most beneficial

2.   What aspects of the assignment, if any, did you find the least beneficial?

I felt like I spent most of the time trying to figure out how to use the software and make sure it was running correctly. There was a point when the temperature sound would not stop playing (even after I stopped the music) so I had to exit the program and reopen the sonification file.

3.   How would you improve this assignment in any way?

I think maybe clearer instructions on how to use the software (maybe with more images). Or explaining more what to expect (not necessarily with the changing kp, ki, kd but rather stating what you should listen for when running the file)

4.   Additional comments?

My main comment is that I found the software relatively difficult to use, at least at the start. Conceptually, I think the idea is really cool and could be really useful. I don't feel as though I learned much more than I previously did because I have experience in PID controls due to Unit Ops.

Student 20

Please enter your results for KP, KI, and KD
KP: 135
KI: 0.2
KD: 250

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 7
Aural: 5
Read/Write: 2
Kinesthetic: 2

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")

1.   I consider myself to be an auditory learner.
                1   2   3   4   5
2.   I consider myself to be a visual learner.
                1   2   3   4   5
3.   I found the instructions for the assignment to be clear
                1   2   3   4   5
4.   I found the software to be simple to use.
                1   2   3   4   5
5.   Before using this software, I had an understanding of PID Control.
                1   2   3   4   5
6.   After using this software, I feel that my understanding of PID Control improved.
                1   2   3   4   5
7.   Before using this software, I had an understanding of Multiple Steady States.
                1   2   3   4   5
8.   After using this software, I feel that my understanding of Multiple Steady States improved.
                1   2   3   4   5
9.   I found the auditory component of the assignment to be helpful in conveying the information presented.
                1   2   3   4   5
10.   I found the visual component of the assignment to be helpful in conveying the information presented.
                1   2   3   4   5
11.   I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.
                1   2   3   4   5

Please answer the following questions in the space provided below:

1.   What aspects of the assignment, if any, did you find the most beneficial?

One of the most beneficial things I think that helped with this assignment was providing the background reading in so many different forms. You used text, equations, and charts all very nicely, which allowed for each specific type of learning to be able to understand the material a little bit better, especially since it was brand new.

2.   What aspects of the assignment, if any, did you find the least beneficial?

The part that I found the least beneficial may have been the all the text that was used to describe the Riggs-Tuning Method. It was a lot of text and a lot of questions in a very small paragraph, making it overwhelming because I have not really had a deep understanding of controls yet. The Max Patcher didn't really seem to help me as much as the graphs that were generated did.

3.   How would you improve this assignment in any way?

If you could, I would provide some examples some of the graphs you generate (without any numbers if need be), just so that way, someone can know if what they're doing is on the right track. For me, I had trouble thinking what I did was right and I feel like other people would feel the same way with so much text thrown at them that they just second guess their results a lot.

4.   Additional comments?

Overall, I think this is a really cool concept and I really enjoyed being a part of this MQP

Student 21

Please enter your results for KP, KI, and KD
KP: 100
KI: 0
KD: 0

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 16
Aural: 14
Read/Write: 12
Kinesthetic: 13

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")

1. I consider myself to be an auditory learner.
   1   2   3   `4`   5
2. I consider myself to be a visual learner.
   1   2   3   `4`   5
3. I found the instructions for the assignment to be clear
   1   2   3   `4`   5
4. I found the software to be simple to use.
   1   2   3   `4`   5
5. Before using this software, I had an understanding of PID Control.
   1   2   3   `4`   5
6. After using this software, I feel that my understanding of PID Control improved.
   1   2   3   `4`   5
7. Before using this software, I had an understanding of Multiple Steady States.
   1   2   3   `4`   5
8. After using this software, I feel that my understanding of Multiple Steady States improved.
   1   2   3   `4`   5
9. I found the auditory component of the assignment to be helpful in conveying the information presented.
   1   2   `3`   4   5
10. I found the visual component of the assignment to be helpful in conveying the information presented.
    1   2   3   4   `5`
11. I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.
    1   2   `3`   4   5

Please answer the following questions in the space provided below:

1.   What aspects of the assignment, if any, did you find the most beneficial?
I think the graph from the program and the background reading are nice.

2.   What aspects of the assignment, if any, did you find the least beneficial?
I think auditory learning is good, but in this case, it may not be very helpful to all learners. Since I am not familiar with the keys or notes of music. When you talked about C notes, I was confused. I was able to figure out the effect of each component from the audio when I tried more values.

3.   How would you improve this assignment in any way?

4.   Additional comments?

Student 22

Please enter your results for KP, KI, and KD
KP: 90
KI: 0.015
KD: 120

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 12
Aural: 7
Read/Write: 9
Kinesthetic: 9

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer
to each question. (1 being "strongly disagree," 5 being "strongly agree")
1.   I consider myself to be an auditory learner.
                        1   2   3   4   5
2.   I consider myself to be a visual learner.
                        1   2   3   4   5
3.   I found the instructions for the assignment to be clear
                        1   2   3   4   5
4.   I found the software to be simple to use.
                        1   2   3   4   5
5.   Before using this software, I had an understanding of PID Control.
                        1   2   3   4   5
6.   After using this software, I feel that my understanding of PID Control improved.
                        1   2   3   4   5
7.   Before using this software, I had an understanding of Multiple Steady States.
                        1   2   3   4   5
8.   After using this software, I feel that my understanding of Multiple Steady States improved.
                        1   2   3   4   5
9.   I found the auditory component of the assignment to be helpful in conveying the information presented.
                        1   2   3   4   5
10.   I found the visual component of the assignment to be helpful in conveying the information presented.
                        1   2   3   4   5
11.   I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.
                        1   2   3   4   5

Please answer the following questions in the space provided below:

1.   What aspects of the assignment, if any, did you find the most beneficial?
The inclusion of almost all learning methods possible

2.   What aspects of the assignment, if any, did you find the least beneficial?
I found all the aspects to be beneficial but the visual aspect to be the MOST beneficial.

3.   How would you improve this assignment in any way?

4.   Additional comments?
Personally, I found the explanation of PID controllers very useful as I'm currently taking chemical process dynamics and control; and, we have been specifically talking about PID controllers this week.   So, it was a great coincidence and I just wanted to say thank you for such an explanation.

Student 23

Please enter your results for KP, KI, and KD
KP: 40
KI: 0.1
KD: 0

Please enter your VARK Preliminary Survey Scores next to each learning mode
Visual: 15
Aural: 3
Read/Write: 4
Kinesthetic: 8

Please read the following statements and evaluate them on a 5-point Likert Scale. You may highlight your answer to each question. (1 being "strongly disagree," 5 being "strongly agree")

1. I consider myself to be an auditory learner.
   1   **2**   3   4   5
2. I consider myself to be a visual learner.
   1   2   3   4   **5**
3. I found the instructions for the assignment to be clear
   1   2   **3**   4   5
4. I found the software to be simple to use.
   1   **2**   3   4   5
5. Before using this software, I had an understanding of PID Control.
   1   2   3   4   5
6. After using this software, I feel that my understanding of PID Control improved.
   1   2   **3**   4   5
7. Before using this software, I had an understanding of Multiple Steady States.
   1   2   3   4   5
8. After using this software, I feel that my understanding of Multiple Steady States improved.
   1   2   **3**   4   5
9. I found the auditory component of the assignment to be helpful in conveying the information presented.
   1   **2**   3   4   5
10. I found the visual component of the assignment to be helpful in conveying the information presented.
   1   2   **3**   4   5
11. I think that it would be beneficial to teach other engineering concepts with auditory-learning methods.
   1   **2**   3   4   5

Please answer the following questions in the space provided below:

1.   What aspects of the assignment, if any, did you find the most beneficial?
The explanation of the PID and MTS

2.   What aspects of the assignment, if any, did you find the least beneficial?
Nothing because all the assignment seems to be integrated together perfectly

3.   How would you improve this assignment in any way?
Try to improve the visual graph and make it dynamic so we can see the change in T

4.   Additional comments?
Thank you very much.