Creation of an Expert System for Teaching Piano Lessons

1987

Carol Chew
University of Central Florida

Find similar works at: https://stars.library.ucf.edu/rtd

University of Central Florida Libraries http://library.ucf.edu

Part of the Industrial Engineering Commons

STARS Citation

https://stars.library.ucf.edu/rtd/5035

This Masters Thesis (Open Access) is brought to you for free and open access by STARS. It has been accepted for inclusion in Retrospective Theses and Dissertations by an authorized administrator of STARS. For more information, please contact lee.dotson@ucf.edu.
THE CREATION OF AN EXPERT SYSTEM FOR TEACHING PIANO LESSONS

BY

CAROL CHEW
B.S., University of Pittsburgh, 1979

RESEARCH REPORT

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Operations Research in the Graduate Studies Program of the College of Engineering University of Central Florida Orlando, Florida

Summer Term 1987
ABSTRACT

Combining the arts with science and technology has had many beneficial results. Computers and music have been connected for many years. Computers have been used in music composition, electronic keyboards, music publishing and digital sound processing. Artificial intelligence has been used in creating expert systems for training people in various fields. An attempt will be made to tie together expert systems for training with current computerized music technology.

This research report proposes that an expert system be developed to teach piano lessons. The fields of music and artificial intelligence will be drawn upon in developing this expert system structure. While existing technology makes the choice of an electronic keyboard the logical one, using an acoustic piano will also be addressed.
# TABLE OF CONTENTS

| LIST OF TABLES | ............................................................. | v |
| INTRODUCTION | ............................................................. | 1 |
| THE PROBLEM | ............................................................. | 3 |
| Identification of Need | ............................................................. | 3 |
| Defining the Problem | ............................................................. | 5 |
| THE SYSTEM AND USER REQUIREMENTS | ............................................................. | 8 |
| The System Requirements | ............................................................. | 8 |
| The User Interface | ............................................................. | 20 |
| APPLICABLE CURRENT TECHNOLOGY | ............................................................. | 25 |
| Personnel Required | ............................................................. | 25 |
| Technology of Musical Sound | ............................................................. | 26 |
| The Musical Instrument Digital Interface | ............................................................. | 32 |
| Computerized Display of the Music | ............................................................. | 34 |
| Past Systems of Interest | ............................................................. | 35 |
| THE PROPOSED EXPERT SYSTEM | ............................................................. | 42 |
| The Domain Knowledge Base | ............................................................. | 44 |
| The Inference Engine | ............................................................. | 53 |
| The Architecture | ............................................................. | 58 |
| IMMEDIATE FEATURES VS. FUTURE ENHANCEMENTS | ............................................................. | 60 |
| SUMMARY | ............................................................. | 64 |
| FURTHER RESEARCH NECESSARY | ............................................................. | 65 |
| APPENDICES | ............................................................. | 68 |
| A. Reading Musical Score from a CRT | ............................................................. | 69 |
| B. Frequencies of the 88 Piano Keys | ............................................................. | 71 |
| C. Digital Sound Sampling | ............................................................. | 73 |
| D. Unit Generators of Music V | ............................................................. | 75 |
| E. Kurzweil 250 Digital Synthesizer | ............................................................. | 77 |
| F. System Configured with a MIDI | ............................................................. | 79 |
| G. Sample Musical Score Report | ............................................................. | 81 |
| H. Stanford CAI Teaching System | ............................................................. | 83 |
| I. Three Parts of an Expert System | ............................................................. | 85 |
| J. Three Knowledge Base Structures | ............................................................. | 87 |
| K. Envisioned Expert System Design | ............................................................. | 89 |
| L. Envisioned Expert System Architecture | ............................................................. | 91 |
LIST OF TABLES

1. Knowledge Base Subsets .................................... 53
2. Inference Engine Functions ................................. 57
3. Expert System Piano Teacher Requirements ........... 63
INTRODUCTION

Combining the arts with science and technology has had many beneficial results. Computers and music have been connected for many years. Computers have been used in music composition, in electronic keyboards for performance, in music publishing and in digital sound processing. Artificial intelligence (AI) has been used in creating expert systems for training people in various fields. Some examples include intelligent tutoring systems such as for medical diagnosis training systems, discussed by Clancey (Hayes-Roth 1983) and in SOPHIE, an electronic troubleshooting training system, discussed by Brown, Burton and Bell (Hayes-Roth 1983). An attempt will be made to tie together expert systems for training with current computerized music technology. This research paper proposes that an expert system be developed to teach piano lessons. The fields of music and artificial intelligence will be drawn upon in developing this expert system structure. While existing technology makes the choice of an electronic keyboard the logical one, using an acoustic piano will also be addressed.

There has recently been some relevant research in bringing together AI with music and in connecting
computerized systems with musical training, but there still exists much room for continued pursuits. Roads provides an overview of four areas of musical research which have a need for AI techniques (1985). He then surveys recent work with AI and music. Dannenberg discusses several programs that exemplify various approaches to instructional computing in music (1987). He outlines problematic areas with music-related software development. IBM is developing an expert system for teaching music theory. An overview of these recent developments will be given in this paper.

In the Problem section, I identify the need for an expert system piano teacher and define the problem which such a system would solve. Discussed next are the system and user requirements for such a system in the System and User Requirements section. The Applicable Current Technology section discusses required personnel to build such a system, the technology upon which it would be built and some relevant systems built in the past and currently under investigation. The Proposed Expert System section describes what the knowledge base, inference engine and architecture of such an expert system should include. I conclude with a division of immediate requirements versus future enhancements, a summary and suggestions for further research.
THE PROBLEM

Identification of Need

One of the reasons to write an expert system is to allow the knowledge of one (or several) experts in a chosen field, to be built into the system, so that this knowledge can be disseminated to a wider population than the expert humans can reach. Concert pianists are often too busy touring the world giving concerts to teach very many students, if any. By building their knowledge into an expert system, there would be no limit as to the number of piano students the resultant expert system could teach. It is hoped that this system could be built using the knowledge and skills of the great concert pianists, such as Vladimir Horowitz, Artur Rubinstein, Vladimir Ashkenazy and Cladio Arrau (to only name a few). This would allow the piano student to experience piano lessons almost as if these great musicians were right in the student's home. Without such a system, it is impossible for most of the world's piano students to ever have such an opportunity, due to the obvious expense and the inaccessibility of these great pianists.

As in any field which utilizes computers to enhance its capabilities, the goal is not to make human piano
teachers obsolete, but rather to expand the student population they reach.

The users of this system would be piano pupils of all levels, from beginners to those very far advanced. The system would work as a "programmed learning" experience for the student. This means that progress would be at the student's own pace. The student could take several piano lessons a week (or a day), if so desired. This would enable the student to progress more rapidly than under a schedule of weekly lessons. A student needing some extra help, and/or wanting to repeat part of a lesson, could do so as many times as necessary for mastery of the lesson. Help or repetition would be done with the expert system, requiring no human teacher's time.

It is typical in instrumental teaching that a student will repeat an incorrect rhythm pattern for an entire week of practice until knowledge of results come at the following lesson. "Repetition of errors could be reduced through programmed instruction" (Deihl 1969).

Small children are often shy and intimidated by sitting down with a strange adult for a piano lesson. This fear would be eliminated with the expert system piano teacher. Of course, as with any computer system, some children may experience a bit of computer anxiety upon their
first exposure to computers. To minimize this anxiety, the system should be built to be as user-friendly as possible.

Another advantage of an expert system piano teacher is the use of the computerized technology available today. The system could record and provide immediate feedback to the student when a wrong note was played. When several wrong notes are played in sequence, or simultaneously, it becomes difficult for a human teacher to remember them all. The computer could automatically track every mistake, and provide the correct answers to the student.

Defining the Problem

The first step of building any expert system is to identify the problem. The problem in this case is to teach piano lessons. In a typical piano lesson, several things occur. The student plays the pieces practiced in preparation for the lesson. The teacher listens to each piece and provides feedback. The feedback consists of telling the student how to improve the performance of the piece. The student is critiqued on the wrong notes played, the wrong rhythm used, the wrong dynamics, any wrong embellishments, and the interpretation of the piece. Of course, not only wrong things are mentioned. What the student has played right and exceptionally well are also communicated by the teacher.
The teacher may ask the student to play the entire piece before judging, or to just play portions of the piece (sections or lines at a time). This enables the teacher to provide more immediate feedback rather than waiting until the end of the piece. The teacher may play a piece (or a section or line) to demonstrate how it should be played. This could be a new piece that the student has just been given to work on, or a piece the student is practicing but has not mastered.

One job of the teacher is to select pieces for the student to practice. This is based on the student's abilities and current level of playing. A student may be given a book for scale practicing, such as the popular Hanon exercises, and several pieces from different eras (Baroque, Classical, Romantic, Modern, etc.). A typical set of pieces may include Bach, Beethoven, Ravel and Dello Joio (modern). The teacher must also determine when the student has perfected the piece, and can move it to his/her repertoire of accomplished pieces, rather than continue practicing it.

When new pieces are assigned, the teacher has the job of providing recommended fingerings for each piece. (Fingerings tell the student which fingers to use for each note.) A piece of music may be played using an endless variety of fingerings. If the choice of fingerings is obvious, or if it would not affect the playing of a section,
some may be omitted. (Fingerings can influence the speed and interpretation of a piece. Fingers are generally numbered from 1 to 5 on each hand, the thumbs being 1.)

Another role of the piano teacher is to recommend to good students that they enter piano competitions, give recitals or seriously pursue the piano professionally at a music school. This encouragement is based upon the teacher's analysis of the level of talent and proficiency with which the student plays the piano.
THE SYSTEM AND USER REQUIREMENTS

The System Requirements

The problem we have defined is that of teaching a piano lesson. To solve this problem, we will produce a set of requirements that are desirable for an expert system piano teacher.

Level of Instruction

The first requirement is that the expert system control the level of its piano instruction. It should be able to teach the absolute beginning student, the intermediate level student and a very technically proficient, advanced student. Most piano teachers specialize in one of these areas. This is primarily due to the need for a teacher of advanced students to be an expert pianist. One cannot teach a difficult piece unless one has mastered it. (This is no different than the differing levels of mathematical expertise required for a first grade teacher teaching arithmetic and a college professor teaching differential equations. It would be a waste of the student's and teacher's time and money for the teachers to reverse roles.) The expert system should be capable of easily switching from one level to the next, at the request of the student, or upon determination by the system.
Basis for Critique

The second requirement for the expert system piano teacher is that it be capable of controlling the basis for its critique of each piece.

Note-Mode. The acoustic piano keyboard has 88 keys, each of which is a possible note. The piano music tells the student what notes to play and for how long to play each one. Unlike some other musical instruments, such as woodwinds, piano music can have many notes being played simultaneously. When a group of notes is played together, the expert system should be able to discern which notes are correct and which are not.

The student may be judged only by which incorrect notes were played, regardless of any incorrect timing. This is often true when learning a piece. The student may switch modes while practicing a piece. The first mode may be to play all of the notes correctly. It may be necessary to slow down or speed up the tempo, and/or to play some notes with the incorrect rhythm, in order to play every note correctly. The expert system should be able to assume this note-mode; i.e., of ignoring tempo and rhythm, and critiquing the notes played.

Rhythm-Mode. A second mode in which one practices is to concentrate on keeping to the beat, at the expense of the
correct notes. This is often a good way to learn the rhythm of a piece. When playing duets, chamber music or in an orchestra, one must always adhere to the rhythm, even if a note or two are played wrong. If not, each instrument would end up in a different measure, and the result would sound like a practicing studio.

In an expert system piano teacher, this rhythm-mode would allow the student to choose the tempo (the tempo is defined as the number of beats per minute) but require maintaining the time signature. (The time signature gives the type of note which gets one beat and tells the number of beats per measure.) The expert system would then critique any notes that were not played in the correct rhythm, based on the chosen tempo. The rhythm of a piece of music controls how long each note should be played. On the piano, this means for how long the key should be depressed, and the length of rests between notes (time when no notes are played).

Correct Dynamics. The next element to add to the critiquing would be the dynamics. Dynamics control the loudness or softness of each note. Theoretically, each note could be played at a different loudness. In reality, however, groups of notes (within a measure), measures (groups of notes), or phrases (groups of measures) are normally marked with dynamics. Thus, over several notes or measures, the player
is told to increase or decrease the loudness of the music. When first learning a piece, one may completely ignore the dynamics, concentrating on the correct notes and/or rhythm. Then, when the notes and/or rhythm are correct, one adds the changes in dynamics. The expert system should allow the critique of dynamics to be added to the note-mode or the rhythm-mode. There should also be a rhythm-note-mode, which combines critiques on the notes and rhythm with the option of adding a dynamic critique to it. Dynamics on the piano are controlled by how forcefully each key is depressed as well as by using the three foot pedals.

**Interpretation-Mode.** The interpretation-mode is the most difficult to judge, even for a human piano teacher. With the notes, rhythm and dynamics (all of which constitute a pianist's technique), there are definite rights and wrongs. Interpretation of music is much more subjective. Interpretation includes the expressiveness and emotion with which the piece is played. This may include speeding up or slowing down in subtle ways, adding dynamics that are not written in the music, and the use of the three foot pedals. A pianist's interpretation may come from: listening to recordings of a piece by a concert pianist, listening to the teacher's interpretation of the piece, studies of the different periods of music, the style of each composer.
(Baroque, Classical, Romantic, etc.), or the pianist's own heart and emotions.

Considering what comprises interpretation, it would be quite difficult to have a computer judge these subjective nuances and emotions. Interpretation would be the mode to use once the student has perfected the notes, rhythm and dynamics of a piece. It is hard to play a piece interpretively when one is learning it, and it would be hard for the computer to judge interpretation if it was critiquing the rhythm to be mechanically perfect. When playing expressively, the pianist may slow down or speed up as mentioned above, which may be a valid interpretation, but may be judged rhythmically incorrect by the computer. It has been said that creativity is based on intuition, which rests on a person's experience (Zaripov 1969). Programming intuition into an expert system would pose a difficult challenge.

Emotions play a fundamental role in motivation, attitude, attention span, memory and interest. These factors all contribute to music making and listening. A listening model taking emotion into account will have an advantage over one that misinterprets blatantly emotional gestures, concentrates on irrelevant details or misses significant musical moments (Roads 1985).
Keyboards

An electronic keyboard (known as a synthesizer) can easily be connected to a computer through a standard Musical Instrument Digital Interface (MIDI). The technology also exists to use a MIDI with a device that can track the sounds made by acoustic instruments (Powell 1986). Acoustic pianos are great for those that already have one. The sound quality of an acoustic piano has always been difficult to capture in an electronic piano. The "action," as pianists call it, of an acoustic piano is stiffer and more controllable than that of an electronic piano. This allows for more sensitive playing of dynamics, as the keys can be depressed with greater flexibility. There is, however, a new synthesizer, the Kurzweil 250 Digital Synthesizer, which supposedly sounds like a nine-foot concert grand piano, and has the action similar to an acoustic piano keyboard (Morgan 1986). The expert system should be flexible enough to allow either an acoustic or electronic keyboard to be used. This technology will be discussed in more detail in the Applicable Current Technology section.

User-Friendliness

As with any expert system, or computer system in general, regardless of how great the algorithms, heuristics, knowledge base or inference engine, it will never be used
unless it is user-friendly. It is difficult enough to convince the computer-phobic population to try a new expert system or computer system. But once they do, they should have a very positive and exciting experience. With an expert system piano teacher, the piano student should not have to do much more than play the keyboard as with a human teacher.

Both the input and output interfaces should be very easy to use. The system should be flexible enough so that the user can set any input parameter for a given piano lesson, and select any desired output mode. The user's interactions with an expert system piano teacher are detailed in the User Interface section.

Method of Instruction

As mentioned previously, the expert system piano teacher should work as a programmed learning system. The system should be an individually prescribed instruction system that moves at the student's desired pace and provides immediate, useful feedback. The system should use the positive reinforcement techniques of psychologist B.F. Skinner, to commend the student's good behavior. In this case, good behavior is piano music that is played well. This important encouragement will motivate the student to practice more. Since there will be no human teacher to smile, pat the student on the back or put a gold star on the
piano piece that has just been perfected, the expert system must write encouraging messages to the student such as "Don't worry. Mozart had trouble with this piece, too." or "Keep up playing like that and you'll be the next Horowitz!"

Generic

As with the building of any expert system, the more generic the system can be built, the greater the possibility of it being widely used. In the case of an expert system for teaching piano lessons, parts of the system could be built generically enough so it could be used for teaching any musical instrument. The generic portions would be: understanding the musical vocabulary and notation, reading and understanding music, critiquing notes, rhythm and dynamics that are played wrong, and the feedback of the system's critique. The non-generic portions would be: the piano pieces built in its knowledge-base, the style analysis of the great concert pianists, the ability to recommend fingerings and the instructional methods that are unique to a piano. (For example, telling a student how to play a passage faster or how to play a passage louder.)

With other instruments come unique problems. On the piano, a note is either pressed down and played, making a certain frequency, or it is not. On the other hand, with woodwinds and brass instruments, the embouchure of the mouth
determines the sound of the note played. With a string instrument, the position of the fingers on the strings determines the note's frequency. With voice instruction (singing), the range of frequencies of the sung notes, is limited only by the person's range of vocal cords. While creating one note on a piano may be easier than with wind or string instruments, piano music has the unique characteristic of being polyphonic. This means that more than one line of music can be played simultaneously. Our expert system will need a method of allowing polyphonic sound production.

The teaching of other keyboard instruments, such as the organ and the harpsichord, would require only slight variations to the expert system. Another advantage of making a generic expert system is that the simpler the inference engine can be, the more easily the expert system can be built (Hayes-Roth 1983).

Practice

Ideally, the expert system piano teacher should be created for use as a day-to-day practicing aid, as well as a weekly (or whatever frequency of lessons) piano teacher. Why not make use of computerized technology to help the student during practice? One unique problem with learning to play the piano is the synchronizing of the left and right hands.
One normally will learn each hand's part separately, and then try to play both hands together. A great capability would be if the expert system could play the left hand while the student plays the right. Often in practicing, a student will hum, sing or even think the part for one hand, while playing the other. This helps the student learn how the piece will sound while feeling the one hand playing. This is especially true with pieces such as Bach fugues, which may have three or more parts (taken up by only the two hands, of course). The expert system could be asked to play the left hand alone for a few lines, while the student plays the right, or to play the second and third fugal parts for a few lines, while the student plays the first part. This would be a tremendous aid to the student.

There are records available today, such as the Music Minus One series from the Music Minus One Group in New York, which provide music for the instrumental student to play along with. Piano concertos, chamber music, duets and other pieces are recorded with all of the parts playing except for the one part which the student plays (MMO 1976). This form of practicing has proven to be a very educational tool. The Music Minus One series has a limitation which an expert system could avoid. If one has a variable speed turntable and slows down the record, the pitch is changed, causing the student's instrument to be out of tune from the record. This
would not be a flaw with the expert system teacher. The student could vary the tempo at which the accompaniment music was played, to enable slower practicing, and would still be in tune with the student’s instrument.

Another way in which an expert system piano teacher could help the student practice is with a metronome. A metronome is a very useful practicing device and is either battery-run or electric. Its purpose is to beat a specified number of times per minute to help the student keep to the rhythm of the piece. The expert system could include a metronome for helping the student practice to the specified rhythm of the piece of music being practiced. Some musical software, such as the ConcertWare+ package (from Great Wave Software) for the Apple Macintosh, currently contains a visual metronome (Bernardo 1986). This package only provides 14 of the 34 traditional metronome markings. The expert system could contain all of them.

Fingerings

As mentioned earlier, a human piano teacher specifies which fingers are to play the notes of difficult passages. This makes them easier to play. The expert system should have the capability of providing fingerings for these passages. This may be one of the more difficult tasks to build into the system. One human teacher may disagree with
another's fingerings, just as teachers may interpret a piece differently. To build this capability into the expert system, the rules for fingerings must clearly be defined.

Perhaps the human expert concert pianists could provide their recommended fingerings for the domain knowledge of the expert system along with the music for each piece. If so, the expert system would not have to actually decide on the optimal fingerings. Instead, it would rely on the knowledge which was previously provided to it by expert humans.

Repertoire

The expert system should be equipped with the appropriate piano pieces to teach a student at any level. These could be built into its knowledge domain. It should have enough variety to suit the tastes of most of its students. If a student requests a piece below or above his level, the expert system should explain why the student would be wasting time in trying to learn it. The system should also contain appropriate sets of music for auditioning at the great music schools (Juilliard, Oberlin, The New England Conservatory of Music, Curtis Institute, The Eastman School of Music, etc.), should the student decide to pursue music through higher education. The student should also be told, based on his/her performance of the pieces,
the chances for admission to one of these schools. This would provide an incentive to practice harder and prevent false hopes or delusions of grandeur.

The User Interface

The field of education encompasses all types of learning, from large auditorium-filled classes to one-on-one tutoring of a student. Teaching instrumental music falls into the category of one-on-one tutoring. For this reason, the expert system piano teacher must be able to gauge the level of understanding and skill of the student. If the lesson being taught is too simple or too difficult, the level of learning and attention will go down. Therefore, the first interaction between the expert system and the piano student must be to determine his/her level of skill. The system might provide a menu of level choices. If the student is unsure of his/her level, there should be some way the system can determine the proper level. One way to do this would ask the student for the number of years of piano study. The problem with this, of course, is that students learn at different speeds. One student may learn at a rate that is several times that of another student. Another means of judging the student's level would be to provide a list of piano pieces (by composer and composition title) and ask the student if he/she had ever worked on them. Yet another test would be to ask the student to play the music to a certain
piece. Of course, there is a big difference between sight-
reading a piece, and playing one that has already been
worked on. (A student might take two pieces of equal
difficulty and would play one that he/she has worked on
fantastically well, while slowly reading through the other.)
The system must find out whether the student can sight-read.

Once the level has been determined, the lesson can
begin. A history of the student's current and past
repertoire should be maintained by the system, so it will be
prepared to teach each lesson. It is envisioned that during
the lesson, the system would tell the student which piece to
play first. There are two possible ways the system could be
designed to enable the student to play the music. The
simplest would be that the student would play the music from
the paper sheet music or a book of music, as is normally
done with a human teacher.

The second way would be to have a video display screen
(CRT) sitting on top of the piano (with either an acoustic
or electronic keyboard), where the paper music is normally
placed. The music would appear on the screen from which the
student could read it. An advantage provided by the system
displaying the music is automatic page turning. Often with
paper music, a student must stop the music to turn the
pages. See Appendix A. At the start of each lesson, the
student would specify certain parameters. The student (or
the expert system) would specify the mode of critique for
the piece (by note, rhythm, dynamics, interpretation or a
combination), the length of part to be critiqued at one
time, and the tempo at which the piece is to be played. To
set the desired tempo for the student, the system might use
the metronome feature to beat out a measure, as a conductor
of an orchestra would do. Since this is a lesson (versus a
practice session), the metronome would stop after this first
introductory measure. The student would then play the
predetermined length of a piece.

As mistakes are made, the critique (based on the
selected mode) would be fed back to the student immediately.
This output from the expert system to the student could
occur in several ways. If the student has the CRT on the
piano, a red dot could light up over the note, rhythm,
measure, etc. that was incorrectly played. The system would
play the section correctly, so the student could hear the
correct version. The student should be able to repeat the
section, trying to play it correctly. If the student is
still having a problem, the system could give an explanation
to the student (on the CRT) as to how to correct that
mistake.

An alternate method of communication from the expert
system to the student would be a printer. If the student was
using paper music, the printer would print out a copy of the
music with the incorrect notes, rhythm, dynamics (or whatever the critique mode was) marked. The capability to print out music by entire piece or by page currently exists in ConcertWare+ (from Great Wave Software) for the Apple Macintosh (Bernardo 1986). The student would then continue as explained above. Explanations would still be given to the student, either via a CRT (located off the piano) or printed report.

Yet another possibility of feedback could be provided if the keyboard was an electronic synthesizer. Lights above (or on) each key could light up as mistakes were made by the student. In all of these scenarios, the main goal is to provide the piano student with immediate, useful, user-friendly critiquing feedback. As was mentioned earlier, positive feedback should be provided at the same time as negative critiques. Any of the expert system's verbiage to and from the student could eventually be voice-activated as this technology becomes readily available. The spoken voice of the computer would more closely simulate a human teacher than would verbiage on a screen or printed report, thus increasing the system's user-friendliness.

The above scenario would be repeated as often as is required for the expert system piano teacher to finish the piano lesson. Perhaps one lesson would be entirely devoted to one piece. Perhaps portions of several pieces would be
taught during another lesson. This would be at the teacher's discretion (with the approval of the student).

Any new pieces the expert system teacher felt appropriate to introduce during the lesson would be played by the system, with the recommended fingerings provided. Any new sections of pieces would be introduced similarly.

Throughout the lesson, the expert system must be prepared to help the student to learn what was played wrong, why it was played wrong, the correct way to play it and how to play it correctly. The student should be able to progress at his/her own pace, and should also know what was played right, and exceptionally well. The student should be able to leave for lunch and return, at which time the system should know exactly where the lesson had stopped, so it can commence from there. These all are contributing factors to a system's user-friendliness. The system should know when to suggest that the student prepare for recitals, competitions and music school and when to take a break.
Personnel Required

Building an expert system piano teacher would require knowledge from several fields. The fields of electrical engineering, computer science and musical acoustics would be drawn upon in designing the system's hardware architecture. Such hardware experts would verify the proposed architecture connecting computers, synthesizers, speakers, MIDI, printers and keyboards. Specialists in music theory, concert pianists and piano teachers (of both novice and advanced students) would be necessary for supplying the expert knowledge. A knowledge engineer skilled in artificial intelligence and expert systems would work with the knowledgeable experts in extracting their knowledge. Human factors engineers and education specialists would help with the training expertise built into the system and with the user-interface. Computer software programmers would be needed to perform the necessary coding. Testing the system would involve a combination of the expert concert pianists, the potential users (piano students), the software programmers and the hardware experts. Publishing and documentation of users' guides and supporting materials would require appropriate specialists.
Technology of Musical Sound

The technological foundation for building an expert system piano teacher would not be possible without some remarkable advancements in the understanding of music as sound. In the 1950s, Bell Laboratories started pioneering work on the computer processing of sound with investigations into factors contributing to the efficient transmission of speech through telephone lines (Mathews 1987). Early attempts to produce musical sounds from a computer were disappointing, but the evolution from these, into today's sophisticated electronic instruments and related computer programs has had significant impact on many areas of music. These technological advancements were made possible by the study of sound.

The essential physical nature of sound is no more than a pressure fluctuation in the air. This fluctuation, when expressed graphically, is a waveform. The ambient air pressure is plotted against time. Our perception of this sound is based on the translation of the pressure fluctuations into nerve impulses in the ear and our brain's interpretation of these nerve impulses (Mathews 1987). The ratio of the height of a sound waveform that can barely be heard to one that hurts the ear is about one to one million (or about 120 decibels). Music, speech and normal sounds occur in the upper 60 decibels of our hearing range (Moog
Sounds heard as having a definite pitch have waveforms with a nearly periodic variation in pressure. The pitch of a sound is directly related to the frequency of repetition of this variation. A pressure variation repeating itself 440 times per second is a tone with a familiar pitch: the A above middle C on a piano keyboard (Mathews 1987). Appendix B shows the frequencies of all of the 88 keys of a piano.

Music is an arrangement in time of a collection of sonic events normally called notes. What actually hits our ears is the ongoing series of vibrations in the air. We hear individual notes only due to our ears and mind splitting acoustic information into distinct events (Moog 1986). We hear everyday sounds from human vocal cords (when air is exhaled), physical objects colliding and other routine events. Another way that sounds are generated is from vibrations in a loudspeaker, caused by varying the voltage of its electrical input. Given a good loudspeaker with an accurate voltage analogue of a sound's pressure function applied to it, an excellent reproduction of the sound can occur (Mathews 1987).

In 1948 at Bell Laboratories, Claude E. Shannon proved the sampling theorem, which lies at the root of all digital processing, recording and sound generation. The sampling theorem states that "any waveform made up of multiple
components of various frequencies can be exactly described by a sequence of numbers that give the value of the waveform's amplitude at a rate determined by the waveform's bandwidth, or range of component frequencies" (Mathews 1987). This theorem indicates that one second of a sound with a bandwidth of 20,000 hertz (cycles per second) can be exactly recorded if 40,000 numbers, called samples, are collected during the one second. The samples correspond to the evenly spaced, instantaneous values of the sound wave's pressure amplitude (or corresponding voltage analogue). Conversely, producing 40,000 sample values per second could generate any perceptible sound. (20,000 hertz spans the range of frequencies audible to the human ear.) The compact disk provides such a storage-and-retrieval system (Mathews 1987).

Using digital microprocessors found in computers is another method of storing and retrieving huge quantities of numbers for sound-generation. Translating computer numbers into voltages, an essential step in digital sound processing is easily accomplished by analog-to-digital converters. These converters translate an electrical signal into a sequence of numbers proportional to the signal's voltage. Digital-to-analog converters perform the reverse (Mathews 1987).
In digital sound sampling, the sampling rate and the resolution determine the credibility within the domain of sound reproduction. Sound sampling captures a specified number of "snapshots" of a sound that is subsequently played back at rates between 5,000 and 100,000 samples per second to create the original sound (Yavelow 1986). See Appendix C.

In order to synthesize sounds by computer, one must have computer software that can efficiently generate the sequence of binary numbers representing the successive waveform samples. One such piece of software was written by Mathews in the early 1960s. Contained in one of these programs, Music V, are unit generators. These provide stored tables of numbers for generating certain waveforms on command, and lists of notes to specify what is to be played. The most important unit generators are the oscillator, the adder and the multiplier. These unit generators of Music V manipulate numbers in the way that the modular devices in an analog synthesizer manipulate electric voltages. Appendix D shows the unit generators. Input variables control the amplitude of the oscillator, and the frequency of waveform-generating cycles. These can change with time, allowing a rise or fall in amplitude and frequency. This influences the attack and decay which have an important influence on the timbre of a computer-generated sound. A vibrato effect can
be simulated from the adder and multiplier unit generators (Mathews 1987).

Music V uses note lists, which are computer instructions that specify the same information as a note on the staff of a musical score. Note lists are letters and numbers that the computer interprets to tell when a note is to be played, its duration, its pitch, its loudness and what instrument it is to be played on (Mathews 1987). Examples of note lists are shown in Appendix D. By computer, it is now possible to specify the wave form or frequency content of the sound, whether it is random or regular to any degree, whether regular or random vibrato is used and to control the attack and duration of the notes.

Two techniques for synthesizing sound by means of a computer today are the additive (or summation of partials) and frequency modulation (FM). Because FM synthesis requires fewer waveforms to produce richer musical tones, it is more popular than additive synthesis.

The method we have just discussed, synthesizing music by computer, or software synthesis, generates output as digitized audio at a rate many times slower than real time. A rough estimate is a million operations (multiplications and additions) per second of sound per instrument are required. Commonly, an hour may be spent to compute one minute of sound. With this method, the output is stored on
disk as computed, and played later at the intended audio rate to produce sound. Real-time control is essential for an efficient, interactive system for use by musicians. The alternative to software synthesis is the use of special signal-processing hardware or a music synthesizer. The sound would be computed instantaneously in response to a computer's commands. This would enable a live performer to interact in a real-time mode (Dannenberg 1987).

More recent developments utilize digital hardware designed specifically for musical purposes. Since the dramatic drop in the cost of memory chips, several synthesizer manufacturers have stored actual instrument waveforms in sampled form. Digital musical instruments based on chips are in many cases less expensive than some traditional acoustic instruments (Mathews 1987). Synthesizers can have different numbers of voices. An 8-voice synthesizer can produce eight notes simultaneously. For playing piano music, eight voices would be sufficient for most of the piano repertoire. One of the most sophisticated synthesizers available today is the Kurzweil 250 Digital Synthesizer. It is a machine capable of reproducing the subtle tonal complexities of a piano and other instruments. It also allows the creating, editing and performing of new sounds with complete artistic freedom and control. The 250 Synthesizer uses novel data compression
techniques with proprietary algorithms. Containing 88 keys, both the sound and action of the 250 Synthesizer are strikingly similar to a grand piano (Morgan 1986). Appendix E is a block diagram of the 250 Synthesizer. Of interest to us is that actual tones are not recorded. Instead, the key that was struck and how hard it was struck are recorded. Since keystroke events are recorded rather than actual musical pitches, a sequence can be sped up or slowed down. Music can be played and then replayed and edited. The required technology exists today for an expert system to understand music as it was played.

Since we have determined that hardware synthesis must be provided in order to allow real-time interactions, the computer programs written to control the synthesizer should run in real-time as well. These would run interactively, providing immediate feedback to the student. At the same time, we would require storage capabilities, so that critiquing of the music and playing it back are possible. Most programming systems for musical purposes are extensions of LISP, LOGO, C, Pascal and Smalltalk (Dannenberg 1987).

The Musical Instrument Digital Interface

Great news for an expert system piano teacher is the recently developed hardware interconnection scheme with a software specification for the purpose of connecting
electronic musical instruments to a computer. Known as the Musical Instrument Digital Interface (MIDI), it was originally intended to standardize the transmission of control information between various brands of synthesizers. It has become the communications standard protocol for sending and receiving musical-event data between computers and synthesizers (or any musical instrument that uses microprocessors).

Pressing a key of a keyboard on a MIDI-capable synthesizer not only causes a tone to be played, but also transmits data bits on an output cable that identify which key was pressed and how hard it was struck. The MIDI data contains entirely numerical information about the pitch, timing, on-velocity, off-velocity and patch changes. The MIDI enables computer-synthesizer communications in both directions. A MIDI input cable enables note and rhythm information to be sent from the computer to the synthesizer, causing a tone to be played exactly as if one of its own keys had been pressed (Kubicky 1986, Powell 1986 and Mathews 1987). This would work the same with any sound-generating device that was MIDI-compatible. All electronic instruments are now MIDI-equipped due to an agreement in 1985 by manufacturers to make it standard practice.

A useful little device, the MPU-401, was recently created by Roland Corporation. It is a MIDI Processing Unit
which has a half-card interface that fits comfortably into an open slot in an IBM PC into which any MIDI-equipped instrument can simply be plugged (Newquist 1987).

Even better news for those with acoustic pianos is that, in addition to electronic synthesizers, acoustic instruments can use the MIDI to interface with a computer. This is made possible by a device which tracks the sounds of acoustic instruments (including the human voice) and produces MIDI data signals (Powell 1986). This pitch-to-MIDI converter would enable an acoustic piano to interface with the expert system on the computer. To generate sound in the opposite direction, of course, the computer must still be connected to a sound generating device (or must be able to generate music itself). This capability would be necessary when the expert system piano teacher performs pieces for the student during a piano lesson. A system configured with a MIDI is shown in Appendix F. Development of the MIDI interface will help with the performance input and sound synthesis aspects of the expert system piano teacher.

Computerized Display of the Music

Music instruction software generally requires a considerable effort to present the subject matter. Musical notation requires a combination of graphics (arbitrary line and curve drawing) and symbolics (use of text and special
symbols display). There are roughly 80 symbols one must understand to decipher a musical score. Forty of these symbols are used frequently. Notation of music is complex and open-ended. Most programs for music instruction add special purpose music notation interfaces, which are not applicable in other areas (Dannenberg 1987).

There are systems which display a musical score to the student, such as The Piano Practicer project at Carnegie-Mellon University (Dannenberg 1987). As well, there are systems which print a musical score such as the ConcertWare+ (from Great Wave Software) for the Apple Macintosh, which allows printing of individual voices or any combination of voice parts. See Appendix G for a sample report.

The Stanford Artificial Intelligence Project has devised a complete music graphics system which utilizes a Digital Equipment Corporation PDP10 computer with CRT display terminals and a Calcomp printer. Allowing complete visibility of all work done, many problems connected with the musical symbols of various size and shape and spacing details can be automatically handled (Smith 1973).

Past Systems of Interest

A Computerized Music Teaching System

In 1967, Stanford University developed and tested a computer-assisted teaching system for the musical task of
sight-singing. The system consisted of an IBM 1620 computer, a typewriter input and output device, an experimental pitch extraction device and a 4-channel tape recorder with search capabilities. Also attached was a microphone, a loudspeaker and a card-reader. The heart of the system was the pitch extraction device, which used an inaudible model tone to pick out successive peaks of the fundamental frequency (Allvin 1967). Appendix H gives this system's architecture.

This system was tested at San Jose State College in California. The test results of this musical Computer-Aided-Instruction (CAI) system demonstrated several advantages of the system, which would also be provided by an expert system piano teacher. The range of level of student taught made it a useful system for grade school music students to professional musicians. The self-paced mode of instruction enabled students to progress faster than with a human teacher. An interesting benefit was that students tried to "best" the machine. "The motivation of working with a machine in order to match or out-do its performance may be one of the most important factors contributing to the success of this kind of learning situation." (Allvin 1967). The system rewarded the student with "Congratulations" when praising performances without error. This showed the emotional involvement which cannot be overlooked as a factor in developing such a system.
Artificial Intelligence Applied to Musical Problems

Suggesting musical applications of artificial intelligence is not new. One application is the keyboard transcription problem, in which the musician improvises on a musical keyboard. The computer's task is to read the keyboard input and produce a printed transcription of the performance in musical notation. The low-level part of this task, that of recording the time of key depressions and their durations, was developed in the eighteenth century by Pere Engramelle. Two centuries later a computerized keyboard transcription system which uses a minicomputer to scan an organ manual, capture keystrokes and display rudimentary music notation was created.

Then, in 1983, a Japanese electronic keyboard arose which offers automatic music transcription on the same device. When playing with a metronome, the transcription problem is solved. However, when more voices are added or rhythmic complexity is added, near-perfect transcription without a metronome is a deep AI-level problem (Roads 1985). One of the AI transcription issues is that interpretation and musical judgement are required due to the inherent ambiguities of common music notation. "To some degree then, an advanced transcription program must be endowed with the
kind of aesthetic judgement formerly associated only with human musicians" (Roads 1985).

Roads surveyed AI applications that help in music: composition, performance, theory and digital sound processing. Instrumental instruction of music is not directly addressed, but some of the suggested uses of AI could apply to an expert system piano teacher.

In composition, it is suggested that the AI knowledge representation techniques could prove useful in capturing the music and information that is currently stored in note lists and is stripped of syntactic and semantic attributes. In computer performance of music, it is suggested that AI techniques could be used to track tempo or listen for other musical cues, adding flexibility and spontaneity. In music theory, current computer-based models of musical structure lack the ability to infer concepts from partial descriptions. Suggested is the use of the AI knowledge-based systems in which searches in the input data are aided by domain-specific knowledge.

For digital sound processing, intelligent digital sound-editing techniques could provide automatic recognition of musical structure, parsing out individual lines in a polyphonic texture and of changing the pitch, starting time, duration, amplitude, articulation, spatial location or
timbre of individual notes, measures, lines or phrases. As for the musical user-interface issue, a traditional passive database approach was proposed by the SSSP group in Toronto, who developed one of the more elaborate graphical interfaces to a music system. AI representations for multiple active knowledge sources based on message passing could improve the problem. Roads states the core of the technical problem in all of these musical areas to be the development of the proper internal representation for the musical domain (1987).

The Piano Practicer project at Carnegie-Mellon University uses knowledge about performance to provide a student with an evaluation of notes that were played with incorrect pitch or played early or late. The computer can play back the recorded performance to show the student what was played wrong, and the correct version of the piece. The computer has the ability to record the exact timing of the performance, and to mark wrong notes and rhythm. This system displays the score for the student to perform (Dannenberg 1987).

Also underway at Carnegie-Mellon University is the Musician's Workbench project. This system is to be an integrated environment for music instruction, composition, performance and research. The architecture of this system is based on a UNIX (copyright) work-station with music software
and hardware. Connected hardware includes a MIDI interface, a Sensor Frame for gesticulative control and a Bradford Musical Instrument Simulator for sound synthesis.

One of the keys to this system is a flexible and extensible data structure for music representation, allowing synergy among various software components. The extensibility keys are the property lists and self-typing data used. Property lists are lists of attribute-value pairs, through which new information can be added to a score without affecting existing software. Examples of attribute-value pairs would be [pitch: F Shelby], [duration: quarter] and [instrument: flute]. Simply adding new properties to the notes would enable the enhancing of the system with new capabilities. Keeping track of right and wrong notes could be accomplished by adding new properties to the notes, such as [evaluation: right] (Dannenberg 1987).

IBM has recently developed an expert system for teaching music and music theory. THE MUSES (THEory of MUSic Expert Systems) is a computerized music theory professor. An interactive system with multiple windows, it is written in Turbo Pascal, is being rewritten in C, runs on an IBM 30XX mainframe connected to a PC with an MPU and a Casio CZ-1000 synthesizer. The graphics are controlled by IBM's Graphical Data Display Manager via a 3179 Graphics Terminal. The
multiple windows allow the access of learning, drill and test sessions as well as a help facility (Newquist 1987).
THE PROPOSED EXPERT SYSTEM

One of the generic categories of knowledge engineering applications is Instruction, defined as "diagnosing, debugging and repairing student behavior" (Hayes-Roth 1983). These expert systems typically begin by constructing a hypothetical description of the student's knowledge that interprets the student's behavior. Then they diagnose weaknesses in the student's knowledge and identify an appropriate remedy. Lastly, they provide a tutorial interaction intended to convey the remedial knowledge to the student. All of these functions should be part of our expert system piano teacher. One might ask why build an expert system in lieu of just a Computer-Aided-Instruction (CAI) system. The need for the AI solutions to problems, such as subjectively analyzing a student's interpretation of a piece, providing fingerings for passages, or comparing the style in which the piece was played to a specific concert pianist, demonstrate the need for an expert system. Determining when a student has perfected a piece, when to apply to a music school and providing fingerings for pieces are other tasks that would call for an expert system.

There are several reasons to apply an expert system to interactive music instruction. A very mathematical and
symbolic field, music theory includes the visual representation of notes, staves, sharps, flats and other symbols—a perfect example of symbolic representation. In addition, music theory is based on the mathematical parameters of values, beats, measures and time signatures. Music theory is based on a rigid structure of information and rules that could be built into an expert system (Newquist 1987).

A typical expert system is comprised of three parts: a knowledge base, an inference engine and a user interface. See Appendix I. What sets an expert system apart from artificial intelligence is the strength of its knowledge base. Before expert systems, artificial intelligence had leaned towards strong inference with a weak set of data. Unique to expert systems is a large and accurate database with weak inference. An expert system piano teacher should have a strong, well-built knowledge base with a piano-specific domain. Its inference engine should be weak and generic, enabling its use for any instrumental instruction. One could simply alter the knowledge base for use with a different instrument. Parts of the knowledge base would be generic, while others would be specific to the piano. Having already discussed the envisioned user interface for an expert system piano teacher, attention will now be directed toward the knowledge base and inference engine.
The Domain Knowledge Base

The knowledge base of an expert system contains the facts and rules of the specific domain being addressed. In real-world applications, the system's knowledge base must also have a framework that organizes these facts and rules and infers new information about the model (Fegreus 1986). Thus the first step in building an expert system is to acquire the knowledge for the knowledge base.

The Knowledge Acquisition Phase in building an expert system is the transfer and transformation of problem expertise from some knowledge source into a program. Sources of the knowledge can be expert humans, books, databases and human experience. To build an expert system piano teacher, one must take the knowledge possessed by human piano teachers and concert pianists and build it into the system. There are many forms of knowledge which are involved: knowledge about music, knowledge about playing the piano, knowledge about teaching the piano, knowledge about concert pianists' playing styles, knowledge about the student, knowledge about education and training and knowledge about communication. Even knowledge about human intuition and creativity should be included.

Knowledge about music should include music theory. This would encompass a musical vocabulary, such as provided
by a musical dictionary of definitions of notes, sharps, flats, scales, keys, rests, chords, measures, tempo, dynamics, etc. This knowledge is a foundation for a human piano teacher to understand the piano. The expert system must understand these elements enough to explain them to a student. Also included should be knowledge about different periods of music (Classical, Baroque, etc.) so that a suitable repertoire of pieces for a lesson are selected. This knowledge about music would comprise a generic part of the knowledge base, since it would apply to the teaching of any instrument.

Specific to the piano in the knowledge base would be the piano music repertoire. The system must be well-versed in piano literature to be able to communicate with the student in any musical period, any composer and at any level. The musical scores must reside in the knowledge base in the same form as their paper counterpart. This would enable their being displayed to the student to play them. The musical scores should contain a common format of: composer's name, piece's name and/or Kirshel listing, the period the music falls into (Baroque, etc.), the difficulty level of the piece, the score in the standard music notation and the note list translation of the score. Stored in this manner, the system could access the information by composer or by level of difficulty as required during a lesson.
A key element of musical knowledge is how to read music. Technology is not yet to the point where the computer can read music visually. The closest to this is a Japanese robot, named Wabot-2 developed at Waseda University. Through visual channels (a high resolution video camera and frame buffer), the robot takes 10-15 seconds to completely scan and recognize a musical score and plan all body movements. It then performs the piece, using two hands and two feet on a digital organ. The robot can recognize limited spoken phrases, but cannot understand musical sound, even its own performance (Roads 1985). Until the day comes when computers can quickly, easily read music visually from scores, a translation of notes into numbers is necessary. The music must be somehow converted from a musical score into the note list type of storage (mentioned in the Current Applicable Technology section).

There are several possibilities for building the musical repertoire into the expert system. Since the technology exists to translate musical pitches, durations and loudness into numbers, the computer could build its knowledge base from recordings by the concert pianists. Another way would be to have the concert pianist play the music live, with the pitch-to-MIDI converter creating the note lists as the music is played. Yet another, more tedious task would be to have a person manually look at the
music and build the note lists into the computer from visual inspection. Regardless of the method of translation used, the piano music itself will be a large part of the knowledge base.

For a human, reading music is a different physical process for each instrument played. The physical motions of playing the same note on a piano, flute, violin or trumpet are different. The resulting frequency of the sound is the same. The A above middle C will always be 440 cycles per second. Unlike the human, the expert system's reading music would be the same physical process of converting note lists and other numbers into frequencies creating sound. Therefore, this could be a generic subset of the knowledge base. To create the sounds of each instrument (known as the timbre), the system would use the technology of a synthesizer. The student would inform the expert system the instrument on which the lesson is to be taught.

A repertoire knowledge subset could be loaded for each instrument. From the appropriate instrument's repertoire, the student should be able to select any piece in his/her level for learning. For example, the student may select from 10 Baroque piano pieces at his/her level. A list of the pieces would be provided to the student and the system would play any that were requested so the student could make a selection.
The different pieces of the repertoire could be sold as add-ons to the system, where each would be a piece of software including the musical score, note list and numeric conversion of the score, fingerings and perhaps various famous concert pianists' interpretations of the piece (each as a separate representation).

The next subset of knowledge to build into the system is the knowledge about playing the piano. This should include: interpreting the note lists and generating the correct sounds from them, setting a desired tempo at which to play the music, and controlling the stopping and starting anywhere in the music. The expert system should play the piano as well as the concert pianists. Ideally, the system should be able to play the same piece with different pianists' styles and interpretations. It may be difficult to provide this knowledge in the system. Perhaps recordings of the piece by several concert pianists could be included, with the expert system building note lists from each. Then, a comparison would be made (by the inference engine part of the expert system), once the student's note list information is supplied (by playing the piece), to determine the pianist they most closely emulated.

Another subset of knowledge the system must possess is the knowledge to teach a piano lesson. It seems that this would best be built into the inference engine.
Knowledge about famous concert pianists' playing styles should be included. This would be a piano-specific subset of knowledge. Similarly, the styles of famous flutists, violinists and other instrumentalists could be loaded. The purpose of this is to compare the student's style of playing (as discerned from his/her interpretation) with the great concert pianists. This would provide motivation and allow the student to set and achieve goals.

The three most common structures for maintaining facts and rules in a knowledge base are: attribute-value pairs, object-attribute-value triplets and frames. See Appendix J. The note list information could be stored in attribute-value pairs, such as the property lists suggested by Dannenberg (1987). Property list examples were: for the note's pitch [pitch: C#], for the note's duration [duration: quarter], for critiquing duration [dur-eval: right] and for critiquing pitch [pt-eval: wrong]. Another version could store the frequency of the note as [pitch: 440], meaning the A above middle C. The loudness could be measured in a numbering system as well, [dynamics: 75], on a scale from 1 to 100. A more difficult challenge would be to build interpretation into the property lists. Interpretation cannot be discerned from examining one note at a time. Entire phrases or sections of a piece are interpreted and thus must be judged as such.
Another required subset of generic knowledge is that about each student. The student's musical background should be stored. This would include the number of years of study of any instruments, music theory, voice lessons, etc. These facts would all help the system with its teaching. The level of the student when determined by the system should be stored. The instrument(s) the student requests to study, the past repertoire (pieces of music already studied) for this instrument, the current repertoire (pieces the system has chosen to teach the student), and the progress of the student on this repertoire (how far into each piece the student has learned). As mentioned earlier, both the student's level and his/her pace (speed of progress) should be determined. To gain the best level of learning, the system should teach the student in the optimal bite sizes for him/her. Any pieces of music the student requests to study should be stored. As the student perfects a piece, it should be flagged as such. The student's musical aspirations should be requested. If these goals are to apply to music school in a certain time frame, the expert system should set the pace accordingly. The student should be warned if the goals are not being met. If a goal is to play the music of a certain composer as a certain concert pianist (or whatever instrument) does, this should be considered in the interpretation-critique. To continually improve the system, the student should be allowed to critique the system. Any
positive and/or negative feedback would help the system
developers to make enhancements.

Knowledge about education, training and communication
were mentioned. These generic skills would all be drawn
upon in building the various user interfaces to the system.
The menus, screens, prompting to the user, critiquing
feedback, instructions to improve the playing and the flow
of the system throughout an entire lesson and series of
lessons will be affected by this knowledge. Standard
critiquing techniques of flagging wrong notes, rhythm, etc.
above the music should be built into the knowledge. As the
inference engine is teaching a lesson, it would rely on
these standard libraries to provide feedback to the student.
Specific lesson libraries should be included for each
instrument which would include the remedial knowledge of how
to correct wrong playing. For the specific instrument,
explanations of how to correct the embouchure (wind
instruments) or where to place the bow (string instruments)
to increase the pitch, or how to move the fingers to
increase the speed (piano) are examples of this knowledge.

Generic knowledge about how to teach musical knowledge
would be necessary. This would interface with the generic
music knowledge itself. If a beginning student has problems
understanding different key signatures, rhythm, general
music-reading, etc., the system should have the knowledge to teach these skills.

Human intuition and creativity were also mentioned as requirements for the knowledge base. Programming these subjective traits into any expert system would be difficult. Perhaps studying other existing expert systems that have successfully attempted such tedious tasks would help.

As with any good expert system, this one should know the bounds of its knowledge. It should recognize when it does not know something. This is called metaknowledge, or knowledge about knowledge; knowing what it does not know as well as what it does know.

In summary, the generic portions of the knowledge base, which could be used for any instrumental instruction would be: knowledge about music theory, musical eras, understanding note lists and other numeric representation of musical scores, general knowledge of teaching instrumental lessons, knowledge about the student, knowledge about education, training and communications and knowledge about human intuition and creativity. The piano-specific knowledge would include: knowledge about pianos, knowledge about playing the piano, knowledge about the various concert pianists' styles, knowledge of the piano repertoire, and knowledge of how to teach a piano lesson. This set of knowledge could be replaced with a similar set for any
different instrument. The generic and specific parts of the knowledge base should be easily separable.

Appendix K shows an envisioned system design of an expert system piano teacher with this type of knowledge base. The following table provides the generic and non-generic portions of the knowledge base.

**TABLE 1**

**KNOWLEDGE BASE SUBSETS**

<table>
<thead>
<tr>
<th>GENERIC SUBSETS</th>
<th>PIANO-SPECIFIC SUBSETS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Music Theory</td>
<td>Pianos</td>
</tr>
<tr>
<td>Music Vocabulary</td>
<td>Playing the Piano</td>
</tr>
<tr>
<td>Music Periods</td>
<td>Concert Pianists' Styles</td>
</tr>
<tr>
<td>Understanding Note Lists</td>
<td>Repertoire of Pieces</td>
</tr>
<tr>
<td>&amp; Numeric Representation</td>
<td>Teaching a Piano Lesson</td>
</tr>
<tr>
<td>The Student</td>
<td></td>
</tr>
<tr>
<td>Education &amp; Training</td>
<td></td>
</tr>
<tr>
<td>Communications</td>
<td></td>
</tr>
<tr>
<td>Remediation for</td>
<td></td>
</tr>
<tr>
<td>Teaching Instrumental</td>
<td></td>
</tr>
<tr>
<td>Lessons</td>
<td></td>
</tr>
<tr>
<td>Human Intuition &amp;</td>
<td></td>
</tr>
<tr>
<td>Creativity</td>
<td></td>
</tr>
</tbody>
</table>

**The Inference Engine**

The driving force behind an expert system is its inference engine, which carries out all of the system's reasoning functions. In an expert system piano teacher, if the inference engine could be built generically, with the
knowledge base being partially specialized and partially
generic, the inference engine along with the generic part of
the knowledge base could be used for other instrumental
instruction.

One subset of knowledge which should probably reside
in the inference engine is how to teach a piano lesson (or
other instrumental lesson). "Teach" implies playing all
pieces perfectly, critiquing each piece and providing
fingerings. This must include the skill to discern when
notes, rhythm, dynamics and interpretation are not played
correctly. This would involve the use of the various modes
mentioned in the System Requirements section. These modes of
critiques could apply to other instruments as well. The
ability to compare the student's performance with the
correct performance in its knowledge base must exist. This
comparison would use the note list subset of the knowledge
base for the specific instrument being taught. The
repertoire for that instrument would be drawn upon from the
knowledge base to select appropriate pieces to teach. The
scores for these pieces would be displayed on a CRT so the
students could play them. The system must follow the
student's playing and provide each page of the score in time
for the student to play continuously. The comparison of
what the student played to the correct playing of the piece
requires logic and thus would be part of the inference
engine. Playing the piece correctly for the student would come from the knowledge base, but the critique would come from the inference engine. The interpretation-mode critique of the piece requires special processing by the inference engine—including the use of human intuition, creativity and subjectivity. The system must be able to judge when a piece has been perfected. There must be some flexibility programmed into the system, in case the student never can quite play a piece as well as the system does.

The system must be able to take the student's history file, retrieve the pieces from the system repertoire which the student is practicing or will be starting, allow the critiquing by selected mode and by section of the piece, provide the score to the student with the errors marked, provide the correct score, and play the piece correctly for the student.

For it to be meaningful, useful and accepted, two important conditions must be provided by the expert system. These involve a decision-making process by the system. The system must provide the appropriate repertoire and it must progress at the correct pace. The appropriate repertoire would be determined when the system selected the level at which to teach the student. This would determine the pieces from each musical period (Baroque, Romantic, Modern, etc.) the student would be given to learn. The correct pace would
be more subtly determined. As the expert system begins teaching a student, it must provide tasks that are not too simple or too difficult. If they are, the student would lose interest and not learn as well. Therefore, the lesson itself should progress at the optimal rate. For example, the student should not be given an entire Beethoven sonata (including several movements) to learn in one week. Nor should the student be given only one line of the sonata in one week. The system should be able to exercise judgement as a human would in determining the student's pace.

Another generic capability the inference engine must possess is to switch from lesson to practice mode. In the practice mode, the metronome function must be provided. The system must be able to recognize that if the student wants to practice with a quarter note getting 120 beats per minute, it must provide beat sounds accordingly. The system must be able to draw upon the repertoire of musical scores and find the recommended speed for playing the piece. (Every paper musical score provides such recommendations.)

Another practice capability is playing parts along with the student. This would require the system to stop when the student wants and go back and start midway into the piece. Roads states that Chafe in 1982 notes the complexity of the task for a computer to "start playing at the thirtieth measure" to be "barely imaginable" because of the
amount of processing it would entail (Roads 1985). Providing the complete symphonic background to an instrumental concerto would be generic, whereas playing one of the hands of a piano part would be piano-specific.

The fingering task in piano music could be provided on the scores themselves. This would entail relying on concert pianists or piano teachers to provide them to the knowledge engineers building this part of the knowledge base. The alternative is for the expert system to provide them. Large sets of IF-THEN rules would be necessary for the system to make the judgements as would a human to provide the optimal fingerings.

The following table outlines the generic and the piano-specific functions of the envisioned expert system piano teacher’s inference engine.

**TABLE 2**

**INFERENCE ENGINE FUNCTIONS**

<table>
<thead>
<tr>
<th>GENERIC FUNCTIONS</th>
<th>PIANO-SPECIFIC FUNCTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teaching Instrumental Lessons</td>
<td>Critiquing by Interpretation</td>
</tr>
<tr>
<td>Critiquing by Note-Mode</td>
<td>Style Analysis</td>
</tr>
<tr>
<td>Critiquing by Rhythm-Mode</td>
<td>Providing Fingerings</td>
</tr>
<tr>
<td>Critiquing Dynamics</td>
<td>Hands Separate Practice Mode</td>
</tr>
<tr>
<td>Reporting of Critiques</td>
<td>Orchestra Practice Mode</td>
</tr>
<tr>
<td>Metronome Practice Mode</td>
<td>Orchestra Practice Mode</td>
</tr>
</tbody>
</table>
The Architecture

The proposed expert system piano teacher would require the connecting of various components from today's current technology. It is envisioned that the user (piano student) would interface with the system using: a piano keyboard (acoustic or electronic) for playing the music, a video screen (CRT) on top of the keyboard for reading the music and receiving feedback from the system, speakers for hearing the system play the music and a printer for reviewing printed copies of the music played correctly and the student's version, with mistakes highlighted. There would also be a typewriter keyboard or other input device, on which the student would set the level and parameters for each lesson. This is how the student's interface to the expert system is envisioned.

Not necessarily understood by the piano student would be the equipment interconnections necessary to run the system. The expert system software would run on a computer (PC, mini or mainframe), where the sound synthesizing software would also reside. The pitch-to-MIDI converter (required for an acoustic piano) would feed the sound into the MIDI. The MIDI would be connected to synthesizer hardware for generating real-time sound by the computer, which would be connected to the computer. Speakers and a printer would also be part of the total system.
configuration. There would be overall software connecting the expert system with the MIDI, synthesizer, graphics and printer. Appendix L shows the envisioned system architecture for the proposed expert system piano teacher.

The choice of computer would be based on the core required to run the software. A mainframe could provide the storage and power required, but is not designed for the synchronization of sound and graphics. A PC is limited in storage capacity, yet the PC chip set is capable of generating different tones. These tones are limited in timbre and the variety of tonal and pitch variations and do not compare to a dedicated music instrument like a synthesizer. The solution may be the use of a mainframe, PC and synthesizer together. Portability and cost should be considerations if the system is to have widespread appeal and use.
IMMEDIATE FEATURES VS. FUTURE ENHANCEMENTS

There are some future enhancements envisioned to the specifications already mentioned for an expert system piano teacher. These could be considered as part of the initial system, but if time or money prohibited, they could be added later to the system. Some of them were already mentioned in this document as being a part of the system. To expedite and simplify the building of such a system, it may behoove the creators to leave some or all of these enhancements out of the Mark-I, or Prototype system. The Mark-I could be built first to demonstrate the feasibility of the approach. After testing, initial use and experimentation, a Mark-II version could be built which included the following enhancements.

The interpretation-mode could be difficult to build into the system due to its subjectivity. This could be left out of the initial system. Critiquing a student's notes, rhythm and dynamics would be sufficient for the Mark-I. The analysis of the student's style is another feature which could be added to the system later. In the piano repertoire, this would tell the student if he/she plays Bach like Glenn Gould, Mozart like Alicia de Larrocha or Liszt like Vladimir
Horowitz. (These are some examples of famous concert pianists known for perfecting the music of these composers.)

The practicing-mode of the system (as opposed to the lesson mode) could be added later. This is the capability for the system to play one part while the student plays another. If this would slow down the creation of the system, it could be left out.

Providing fingerings for the piano music could be done at a later time. If the property list method of storing the scores in the knowledge base was used, fingerings could be added to the lists in the future.

Making the system generic where possible should be accomplished. The initial system should include a piano-specific knowledge base, with generic parts and a generic inference engine. Building knowledge bases for other instruments could be done at a later time. Some of the special features of winds, strings and other instruments would require careful attention be given to their knowledge bases.

When the technology is available to allow the system to read the music from visual scanning in an efficient and effective manner, this should be included. This would allow the building of the internal numeric representation of the musical scores (such as note lists) directly from the paper music.
If the keyboard the student was playing on was out of tune, meaning that when an A was played above middle C, it was not at 440 cycles per second, the entire judgement by the system of the correct notes would be wrong. The capability should exist for the system to adjust to an out of tune instrument. (Ideally, the student should not let the piano become out of tune, but this has to be anticipated.)

Ideally, the expert system instrument teacher could be connected to other AI music software, such as that being developed for music theory, composition and transcription. Since similar internal representation would be necessary for any of these systems, why not share the expertise being developed in all of these musical systems. One gigantic musical expert system would enable a student to access any musical aid from one place.

These are some of the features that could be left out of the Mark-I expert system piano teacher to expedite the production of the system. When the time allowed in the future, these capabilities could be added. The following table lists those features which should be considered in the immediate Mark-I system versus those that could be added in the future.
### TABLE 3

**EXPERT SYSTEM PIANO TEACHER REQUIREMENTS**

<table>
<thead>
<tr>
<th>MARK-I REQUIREMENTS</th>
<th>LATER ENHANCEMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piano-Specific Knowledge</td>
<td>All Instruments Knowledge Base</td>
</tr>
<tr>
<td>Base (limited)</td>
<td>Interpretation-Mode Critique</td>
</tr>
<tr>
<td>Generic Inference Engine</td>
<td>Style Analysis by Concert Pianist</td>
</tr>
<tr>
<td>Set Level &amp; Pace of Instruction</td>
<td>Acoustic Keyboard</td>
</tr>
<tr>
<td>Note-Mode Critique</td>
<td>Practicing Aids</td>
</tr>
<tr>
<td>Rhythm-Mode Critique</td>
<td>Supplying Fingerings</td>
</tr>
<tr>
<td>Dynamics Critique</td>
<td>Automatic Reading of Music</td>
</tr>
<tr>
<td>Electronic Keyboard</td>
<td>Automatic Pitch Adjusting</td>
</tr>
<tr>
<td>User-Friendliness</td>
<td>Connection to other</td>
</tr>
<tr>
<td>Programmed Learning</td>
<td>AI music software</td>
</tr>
<tr>
<td>Instruction</td>
<td></td>
</tr>
<tr>
<td>MIDI Interface</td>
<td></td>
</tr>
<tr>
<td>Printed Critiques</td>
<td></td>
</tr>
</tbody>
</table>
SUMMARY

Many recent discoveries have enhanced the possibility of an expert system piano teacher. Electronics, musical acoustics, artificial intelligence and CAI music systems have all laid the foundation for such a system. Also of benefit, has been a growing open-mindedness of the artistic and scientific populations to the value of merging these two disciplines for the benefits of increasing the knowledge of mankind. This paper has drawn upon musical knowledge as well as principles of artificial intelligence in proposing the creation of an expert system piano teacher. The numerous benefits of such a system might compensate for the time, energy and expense of building it. Building the inference engine generic enough to use it for any instrumental instruction, yet supplying the knowledge base with the robust domain of the piano, adhering to piano-specific details, will make the system the most usable.
FURTHER RESEARCH NECESSARY

It is important to stress that before an expert system piano teacher is built, the expert concert pianists and teachers should be consulted. This would ensure that the system is being developed in the most meaningful direction for its eventual users. Piano students should be brought in to walk-through a theoretical piano lesson. Other instrumentalists should be consulted, to test the feasibility of expanding it for use in any instrumental lesson. An expert system could be built with accurate algorithms, a factual knowledge base and a powerful inference engine, but if there is not a user population interested in the system, it may never be used.

It will be interesting to keep abreast of the work at IBM on THE MUSES, at Carnegie-Mellon on The Piano Practicer and The Musician's Workbench, and any future work at Stanford. THE MUSES has combined much of the same hardware that would be needed for an expert system piano teacher, but does not address the problem of instrumental instruction. The Piano Practicer provides critiques of wrong notes and rhythm, but mentions nothing on interpretation or style analysis. The use of property lists to store the attributes of a musical score in The Musician's Workbench would be a
very good model for similar knowledge representation in an expert system piano teacher.

It will be useful to follow developments in the AI music applications outlined by Roads (1985). Especially of interest to our system will be research to help the computer find its place in a musical score. This is a definite problem which must be solved for an expert system piano teacher to be effective. A computer that can read music directly from a score, as the Japanese robot can, in an efficient manner would reduce the initial conversions necessary to build numeric notation using a MIDI device. If such innovation is produced, the note list version of the musical scores could be built directly from any paper copies of the pieces. This would eliminate the need for a MIDI sound interpretation process.

Another area which needs refinement is the computer's interpretation of the musical sound. If one plays with more than a metronome beating of the rhythm, the computer may cut some notes short in its interpretation of what was played. The problem is that a human cannot play the prescribed notes of a musical score precisely on time or for the exact duration indicated. This forces the computer reading the incoming events to make decisions about note values and placement. This is a decomposition process in which the software must make musically appropriate decisions regarding
the player's intentions. Powell discusses Dannenberg's significant progress in the development of real-time heuristic techniques which include algorithms that can actually follow a musician's performance and continuously ascertain the proper rhythmic context speeding up and slowing down as a human accompanist might react to the actions of a soloist (Powell 1986). This information can also be used to draw a screenful of music notation entered via a MIDI host instrument. It would be helpful in the building of an expert system piano teacher to study these algorithms for possible use.

Work on THE MUSES has led to the need for an innovation allowing for the comprehensive inclusion of both sound and graphics to help all computationally intensive future expert systems. Expert systems have traditionally been graphics oriented with little regard for sound, especially more than an electronic beep (Newquist 1987).

The further investigation of the above-mentioned problems and current research could prove very beneficial in the development of an expert system piano teacher as discussed in this paper.
APPENDIX A

READING MUSICAL SCORE FROM A CRT
MUSIC READ FROM A CRT ON A PIANO
APPENDIX B

FREQUENCIES OF THE 88 PIANO KEYS
HIGH FIDELITY SOUND SYSTEM

1000 S.F.S. OR LESS

TELEGRAPH CHANNEL

TELEPHONE CHANNEL

BANDWIDTH

BANDWIDTH

FEMALE VOICE

MALE VOICE

RANGE OF HUMAN HEARING

FREQUENCY IN CYCLES PER SECOND

Audio Frequency Range
APPENDIX C

DIGITAL SOUND SAMPLING
Figure 1: Digital sampling of an analog sound wave: (a) The analog wave; (b) digital samples taken of the wave; (c) digital reconstruction of original waveform.

Figure 2: The number of digital values used to represent samples affects the accuracy of the reproduction of the sound wave. Note the difference in the reconstruction of the waveform, even though the sampling rate is identical.

Figure 3: A minimum of two samples are required to represent a sound wave.
APPENDIX D

UNIT GENERATORS OF MUSIC V
COMPUTER "INSTRUMENT" is constructed from so-called unit generators in the sound-synthesis program Music V, written by one of the authors (Mathews). Unit generators are subprograms whose numerical inputs and outputs can be interconnected. The most important unit generator is the oscillator. Every time an oscillator is cycled it generates a series of numbers that correspond to a preselected waveform. The output waveform's amplitude and the frequency of the waveform-generating cycles are determined by the oscillator's two inputs. The amplitude input of a pitch-determining oscillator often is the output of another oscillator that controls the sound's envelope. The envelope determines the sound's attack (how quickly it builds up), its steady state (its middle part), and its decay (how quickly it fades away). An instrument thus constructed is "played" by means of note lists (bottom left); computer instructions that specify essentially the same information that a note on a musical staff (bottom right) conveys to the performer.
APPENDIX E

KURZWEIL 250 DIGITAL SYNTHESIZER
Figure 1. Block diagram of the Kurzweil 250 Digital Synthesizer, showing the three main microcomputer boards: the central processor, with its on-board Motorola 68000 microprocessor; the channel-group processor, used to extract and combine soundfiles; and the channel output board, which mixes as many as 12 channels of information into 2 and also serves as the input section for the digitizer.
APPENDIX F

SYSTEM CONFIGURED WITH A MIDI
MUSICAL-INSTRUMENT DIGITAL INTERFACE (MIDI) is a protocol for digitally coding musical data that was adopted by manufacturers of electronic instruments a few years ago. It allows a synthesizer to communicate with a computer. In the daton instrument (see illustration on preceding page) analog electrical signals that specify where and how hard the daton surface was hit are converted into binary numbers and passed on to a computer. The computer combines this information with the notes that have been stored in its memory and sends the combined information in MIDI form to the synthesizer, which then plays the appropriate tones.
APPENDIX G

SAMPLE MUSICAL SCORE REPORT
Concerto in D minor (for two violins)
Johann Sebastian Bach (1685-1750)

Now known as a composer, Bach was renowned by his contemporaries as a violinist and organist. This "Bach Double" concerto is a favorite among violinists.

Figure 1: An example of a printout using ConcertWare+’s printing options, which allow full use of margins and varied paper and type sizes.
APPENDIX H

STANFORD CAI TEACHING SYSTEM
APPENDIX I

THREE PARTS OF AN EXPERT SYSTEM
AN EXPERT SYSTEMS MODEL is based on some facet of the real world. Within the system’s three-part structure, the knowledge base stores a collection of facts governed by IF-THEN rules. In turn, the inference engine combines the given facts and rules to deduce new facts. Because expert shells are preprogrammed with this logic, users have to enter only the pertinent data into the knowledge base. Users then view and interact with the model through a terminal, which may provide such features as menus, simultaneous logic traces and graphics.
APPENDIX J

THREE KNOWLEDGE BASE STRUCTURES
Artificial Intelligence

**Figure 2:** Facts and rules in an expert system's knowledge base are usually stored in one of three types of structure: attribute-value pairs, object-attribute-value triplets or frames. Attribute-value pairs do not explicitly allow the connection of attributes to multiple objects, but such a hierarchy can be represented implicitly. Object-attribute-value triplets explicitly represent these hierarchies, but each attribute must be entered as a separate entity. Frames overcome this limitation by providing for named slots that represent all of the attributes of an object.
APPENDIX K

ENVISIONED EXPERT SYSTEM DESIGN
CONTROL MODULE

1) LESSON
2) PRACTICE

INFERENCE ENGINE

LEVEL SELECTOR

if first time on

SYSTEM PLAYS PIECE

SYSTEM PROVIDES SCORE

note-mode

rhythm-mode

dynamic critique

interpretation-mode

FINGERING SELECTION

REPORTING OF CRITIQUES

STYLE ANALYSIS

1) METRONOME
2) NO PRACTICE MODE

Piano Specific Knowledge Base Subsets

Generic Knowledge Base Subsets

Student Data
- level
- past pieces
- current pieces
- goals

Music Theory
Music Vocabulary
Musical Periods

Remedial Instrumental Instructions
Critique Reporting

Repertoire
- scores
- note lists
- composers
- period
- level

Concert Pianists Styles

Piano Knowledge

REVISIONED EXPERT SYSTEM PIANO TEACHER SYSTEM FLOW
APPENDIX L

ENVISIONED EXPERT SYSTEM ARCHITECTURE
System's music played for student

receives feedback

music sheet

reads music

student's music is picked up

saves

REPORTS OF CRITIQUES

printer

sets parameters

IC keyboard

ENVISIONED EXPERT SYSTEM PIANO TEACHER ARCHITECTURE
REFERENCES


MMO Music Group Inc., Music Minus One, 43 West 61 Street, New York, NY 10023.


Bernardo, Mario Sergio. "ConcertWare+ and SongPainter." Byte June 1986.


