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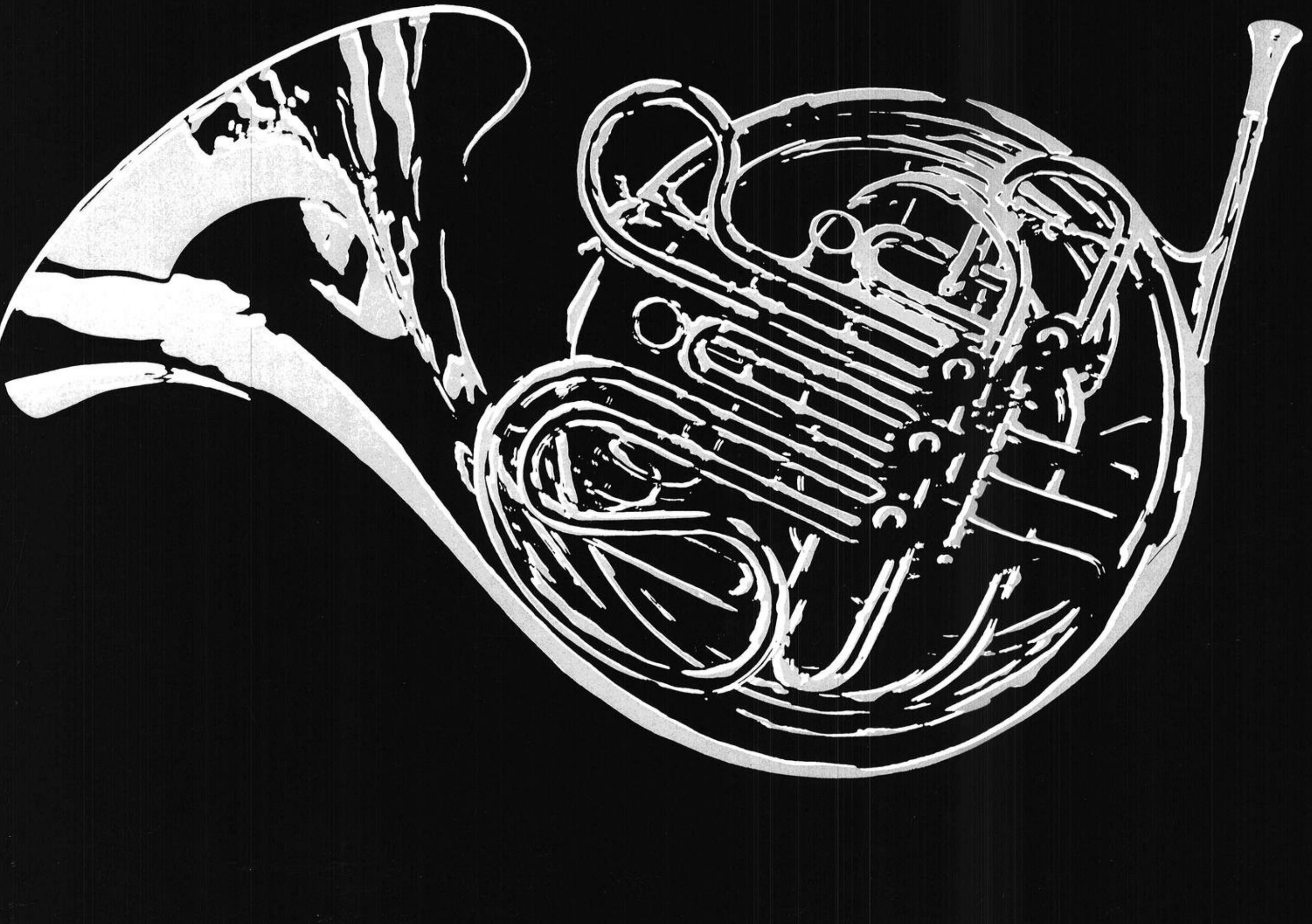
# wisconsin engineer

University of Wisconsin-Madison

## Acoustics
## A sound technology



# wisconsin engineer

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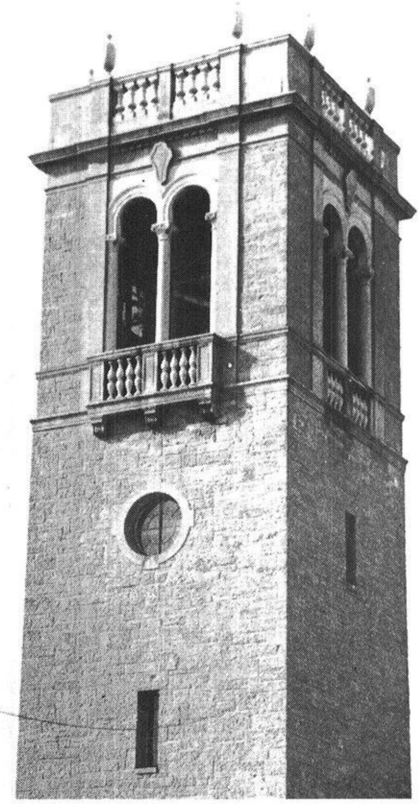


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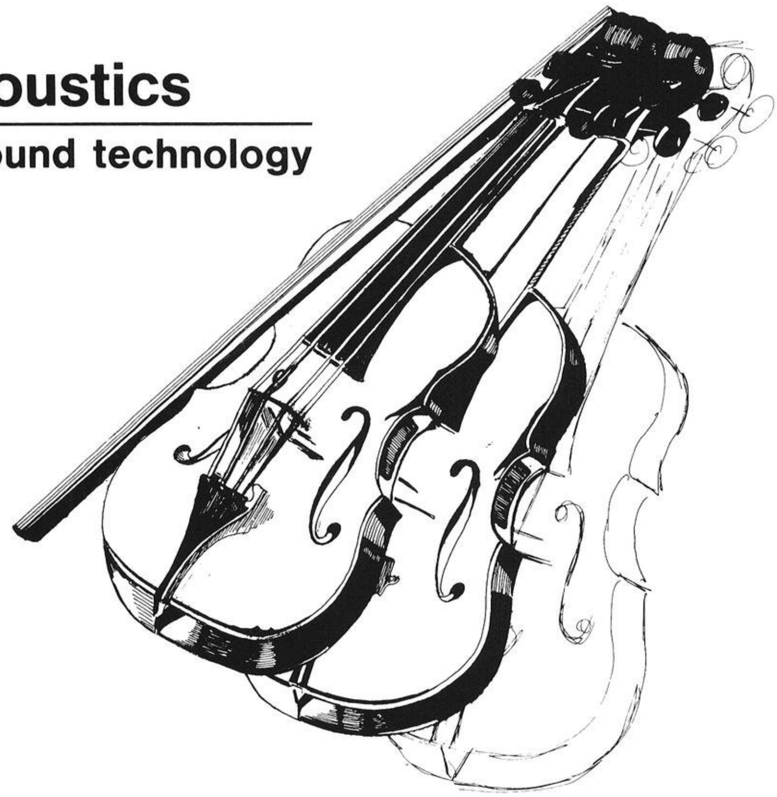
editorial

# Acoustics

## A sound technology

by Michael Pecht



*"Progression of Sound" by Cinthia Conrad–Enrichment of the fine arts through the progression of acoustic technology.*

The University of Wisconsin–Madison has no acoustics department. However, my undergraduate degree at the University is in acoustics. It was an individual major. On the advice of J. L. Flanagan, head of the acoustics research department of Bell Laboratories, I selected courses for my major, in physics, mathematics, computer science, engineering mechanics, electrical engineering and psychology. My friends called me a madman.

I wanted to know everything related to sound. My head overflowed with questions. How does a musical instrument such as a violin or horn produce such rich, complex tones? Why are certain sounds pleasing while others are quite painful? How is an auditorium designed to accommodate a full orchestra playing Wagner or a lecture given by a person with a weak voice?

Some of these questions were answered by my advisor, Professor William Fry of the High Energy Physics department. Besides attending his physics course–"Acoustics for Musicians," I studied independent topics he suggested. Moreover, his enthusiasm and creativity inspired me. For example, it has been known that the richness of a violin's tone increases with age and use. Professor Fry thus subjected some newly-built violins, which he produced, to white noise via a transducer mounted to the violin's bridge. Other violins were bombarded with dosages of radiation equivalent to over 100 years of normal life. Both experiments resulted in noticeably superior-sounding violins.

Profesor Thurlow's "Experimental Psychology of Hearing and Communications" course, taught in the psychology department, exposed me to the human factors of acoustics. In particular I learned that loud, persistent noise produces direct bodily changes such as alterations in blood pressure and heart rate, disturbances of equilibrium and increased gastro-intestinal activity. I finally understand why I am always so hungry!

Other courses dealing with acoustics include those in engineering mechanics on vibration and material properties. The physics and electrical and computer engineering departments offer courses in optics and electro-magnetic field theory with analogies to sound waves. The electrical and computer engineering department also offers an electro-acoustical engineering course. Finally, the mathematics and computer science departments have courses which train an individual in solving appropriate acoustics equations developed in the engineering and physics courses.

This issue of the *Wisconsin Engineer* is on acoustics. Articles include analysis of three musical instruments, the technology behind acoustically balanced auditoriums, and how to acoustically improve your own listening environment. There is also an article concerning the sound the planets generate by orbiting the sun.

You don't need to be a scientist to perceive sound. However, the scientific study of sound has produced everything from car mufflers to musical instruments. I hope the articles in this issue will "strike a note" of intellectual awareness into the beauty of acoustics.

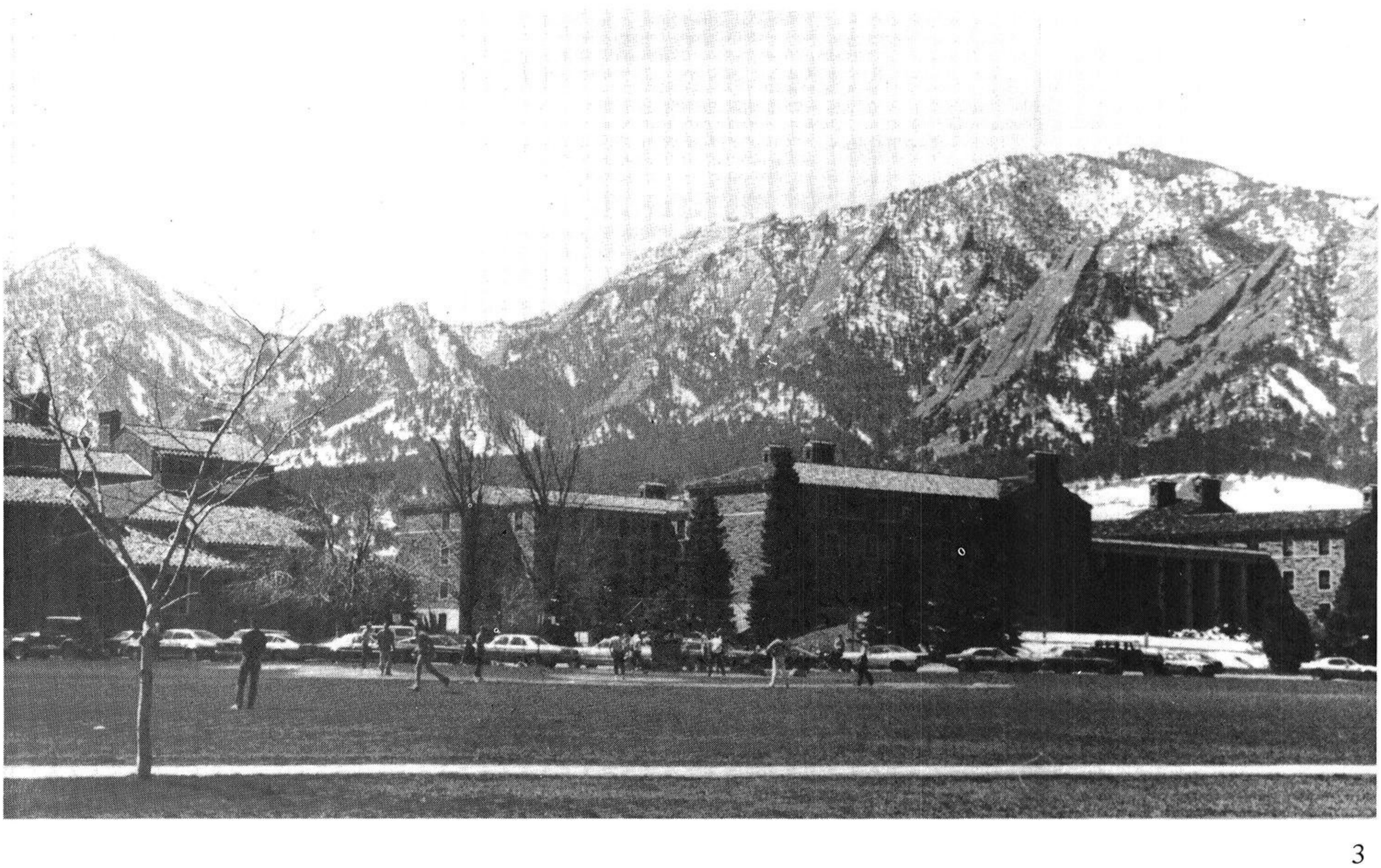
# Wisconsin experiences Rocky Mountain high

by Bob Polasek

For the second straight year, the *Wisconsin Engineer* was named one of the top five college engineering magazines in the nation. During the 60th annual Engineering College Magazines Associated convention this April, attended by approximately seventy-five major universities and cordially hosted by the University of Colorado at Boulder, *Wisconsin Engineer* won awards in six of eleven categories which included editorial content, layout, photography and overall magazine quality. Thanks to everyone who made this possible.

The awards banquet, however, only constitutes a small portion of the ECMA national convention. Professionally instructed magazine seminars acquaint college representatives with methods used by successful editors, writers, photographers and advertisers during the production of their magazines. Instructional seminars are also conducted and supported by ten companies such as IBM, General Motors and Exxon. By far the most rewarding aspect of the convention is meeting and sharing experiences with journalists from a variety of universities located throughout the country. Social activities and exchange sessions are set up to allow representatives to compare and contrast ideas, offer suggestions and, in general, experience different ideas and personalities, leading to many new friendships. Judging by the excellent representative qualities displayed, involvement in collegiate journalism has greatly benefitted all participants. The *Wisconsin Engineer* has a variety of magazine positions available next year. We strongly encourage anyone interested in becoming involved with the magazine and the ECMA to contact the editor.

Along with the previous advantages, the ECMA convention enables students to visit and familiarize themselves with a new part of the country. Boulder, Colorado provided a scenic background for this year's convention.



# The sound of violins

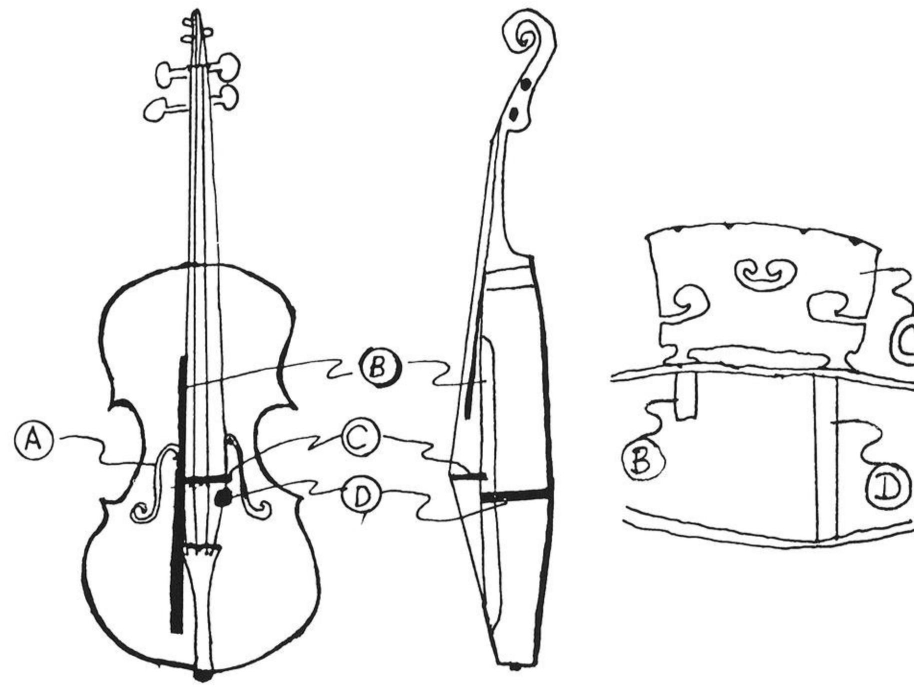
**by Charles Grassl**

*Charles Grassl is a graduate student studying physics at the University of Wisconsin–Madison. His interests include the physics of musical sounds.*

*Early Italian violinmakers apparently understood the complex mechanisms of sound production in the violin and the art of making a violin with rich overtones.*

*The work and experiments of early violinmakers is continued by Professor William F. Fry of the Department of Physics here at the University of Wisconsin–Madison. Professor Fry's experiments on violins have done much to improve our understanding of the principles of violin construction and design.*

The violin, though one of the most complex string instruments, was developed very early in the history of Western music. The inventor of the violin is not known but it may have been Andrea Amati who founded the famous Cremona (Italian) school of violinmakers in the 14th century. Amati died around 1580 but his school lived on. Within about 150 years his descendants and their pupils, most notably Antonio Stradivari and Giuseppe Guarneri, had brought the art of violinmaking to such an extraordinarily high level that it is only now that one dares to dream of equaling or surpassing it. The early violinmakers learned their trade both by experiment and by trial and error. The instruments of Stradivari show definite trends of development throughout his lifetime. The successors of the great violinmakers did caringly preserve the "art" of violinmaking; however without really understanding the principles of violin construction, they could do little to advance the science of violinmaking.




*The violin. (A) f-hole (B) bass bar (C) bridge (D) sound post.*

For the production of sound in the violin we must consider two modes of vibration of the violin body. One mode, called the breathing mode, is important for the lower frequencies. The other, called the rocking mode, is responsible for the higher overtones of the strings.

Consider the construction of the violin (see figure). Underneath the foot of the bridge on the side of the string of lowest tuning is glued a thin strip of wood called the bass bar. A little behind the other foot of the bridge is a cylindrical piece of wood called the sound post which is wedged between the top and the bottom of the violin.

The breathing mode of vibration of the violin body is excited by the fundamental modes of the violin strings. Bowing a note produces a side-to-side force on the bridge exerted by the string. When the force from the string is directed to the right (see figure), the bass bar, which is connected to the left foot of the bridge, will cause the top of the violin to move upward. Meanwhile the right foot of the bridge pushes the bottom of the violin down via the sound post. The com-

bined motion of the top and bottom of the violin draws air into the body through the f-holes. Similarly when the string applies a force to the bridge directed in the opposite direction, air will be forced out of the violin. Thus, the breathing mode of vibration couples energy from the string into acoustical energy in the air.

For the higher overtones of the strings, the motion of the top and bottom of the violin affords too much inertia to be an efficient radiator. In this situation the important mode of vibration changes from the breathing mode to the rocking mode. The mass of the bass bar is important in determining where the cross-over point occurs between breathing and rocking modes. Notice in the figure that the sound post is not directly under the foot of the bridge; rather it is a small distance behind the bridge. For high frequencies the sound post acts as a fulcrum about which the upper and lower parts of the top of the violin rock back and forth. The bass bar is also shaped to aid this rocking motion. The bass bar is thicker directly under the bridge and gets thinner farther away from the bridge. In this way the bass bar has a decreased moment of inertia for rocking motion.

For higher frequencies the wavelengths radiated in air are comparable to the dimensions of the surface of the top of the violin and hence the violin acts as an efficient sound radiator in this range.

The effect of all this on the listener is that even though the overtones have smaller amplitudes than the fundamentals for the strings, the higher frequency sound is radiated away more efficiently. Thus the perception of a high pitch sound from the violin can balance the low tones, producing an intricately complex and rich sound.

# Perfecting the piano

by Lauren Schlicht

*Lauren is a former editor of the Wisconsin Engineer who has returned to school after working with the Wisconsin State Journal.*

The piano as we know it today has evolved into its present form to a large extent because of the practicality of the builders and the needs of the musicians, rather than the principles of acoustical physics. In fact, some early piano designers believed that the sound of the piano came entirely from the sound board, not the strings. Physics may not have played a large role in the development of the piano, but one can use physics to investigate how the instrument deviates from acoustical theory to produce tones that are almost impossible to duplicate.

Major faults in both the clavicord and the harpsicord, both predecessors of the piano, led to the development of the piano. The 15th century clavicord used metal strings stretched across a me tal bridge. The bridge determined the pitch of the string and acted like a sounding board to produce the tone. Since one string could be used to produce several tones, strips of cloth were interlaced through the ends of the shorter section of the strings to damp out unwanted tones. A wide variety of pitch and the ability to execute dynamics, playing either loud or soft, made the clavicord a popular instrument with composers. Unfortunately musicians were called upon to play for larger audiences. The instrument's weak tones and lack of volume made the instrument unsuitable.

Experiments directed toward producing louder sounds led to the longer strings and larger sounding board of the 16th century harpsicord. Hitting the larger strings with a clavicord action, however, did not cause them to vibrate adequately. A plucking motion was substituted for the hitting action. When a key was struck, a jack with a quill mounted at a right angle plucked the strong. As the jack returned to its original position, a damper mounted above the quill stopped the string's vibration. This method had two drawbacks. A string could be used for only one pitch, so more strings and space were needed for the same range of notes. Furthermore, the plucking method made it impossible to vary the loudness.

The piano incorporated the striking of the strings found in the clavicord and the longer strings and larger sounding board of the harpsicord. Bartolommeo Christofori invented the hammer 'action' that gave the piano both the ability to vary a note's loudness and to produce a usable volume level.

The piano and its predecessors work on the simple principle of a stretched string being set into vibration. This vibration is then transferred by a sympathetic response to a sounding board. From there it gets complex. In efforts to bring the instrument nearer to perfection, strings, frame, construction and even the hammer action have been updated with modern materials and skills.

The last major innovation in the piano occurred in 1855 when the American piano manufacturer Henry Steinway developed the grand piano with a cast iron frame. This design permitted the use of strings

that were even larger than the old wooden frames could handle. It gave the sound of the piano much greater brilliance and power.

Most modern pianos have a cast iron frame and steel strings. Wire used for the strings has an ultimate tensile strength of from 300,000 to 400,000 pounds per square inch. To get the bass strings to vibrate slowly enough for a low pitch, the steel wires are wrapped with copper or iron. In a large concert grand piano the strings subject the frame to an average tension of 60,000 pounds per square inch. The strings are anchored through the frame to a tuning pin sunk into the pin block. In order to keep the tension needed for the strings, an average pin block is built up with 41 crossgrained sections of hardwood laminated together.

In an ideal string, vibration is set up by the force that tries to return the string to its original position after displacement. The string will vibrate in its fundamental frequency, as determined by its length, and in higher harmonic vibrations. True harmonic partials have frequencies that are whole number multiples of the fundamental frequency. Strings, especially those found in musical instruments can set up simultaneous vibration, vibrating at the fundamental frequency as well as several partials.

Stiffness in the material make-up of piano strings causes deviations from the behavior of an ideal string. The stiffness of the strings affects the restoring force so that the higher partials generated are not true harmonics of the fundamental frequency. It is this large array of inharmonic partials that give the piano a warm tone that is almost impossible to reproduce electronically.

A piano keyboard usually consists of 88 keys divided into seven and one third octaves. An octave consists of eight white keys and five black keys of sharps and flats for the diatonic scale. The white keys aren't tuned exactly to the diatonic scale. They are tuned to the equally tempered scale, a scale in which an octave is simply divided into twelve equal parts.

In practice the piano is tuned slightly differently. A piano tuned to a pure scale would sound good in only a few keys. According to John Wolozyn, who has been tuning pianos in the Madison area for over 35 years, a scale must be a **little** out of tune to sound good in all 12 major keys. In addition, the lowest octave is usually tuned slightly flat and the upper octaves slightly sharp.

Tuning hasn't changed much in the last century. Usually the tuner has a tuning fork for each note in the octave containing middle C. All but the lowest octaves have three strings for each note; each string has to be in perfect tune with each other as well as the tuning fork. From there the scale is expanded by tuning up and down by four and five note intervals. Inharmonicity is compensated for by expanding all 4ths by three beats per five seconds and contracting all 5ths by two beats per five seconds. The number of beats is equal to the difference in cycles per second between the two tones. The introduced beats which make the note slightly sharp or flat aren't noticeable to the average listener. If the tones are further out of tune, or if the separate strings that make up a note are slightly off, the phenomenon of the beats makes the piano sound 'out of tune'.

This can also occur if two pianos are played simultaneously in close proximity. In the recent Ferrante and Teicher concert at the Madison Civic Center, this was a main concern. Each string in the two pianos used in the concert had to be tuned to each other. Slight variations between the pianos would cause them to sound as bad as if they were actually out of tune. For two pianos to be perfectly in tune they must be the same make and year to guarantee against slight variations in manufacture or materials. A whole day was spent tuning them to each other.

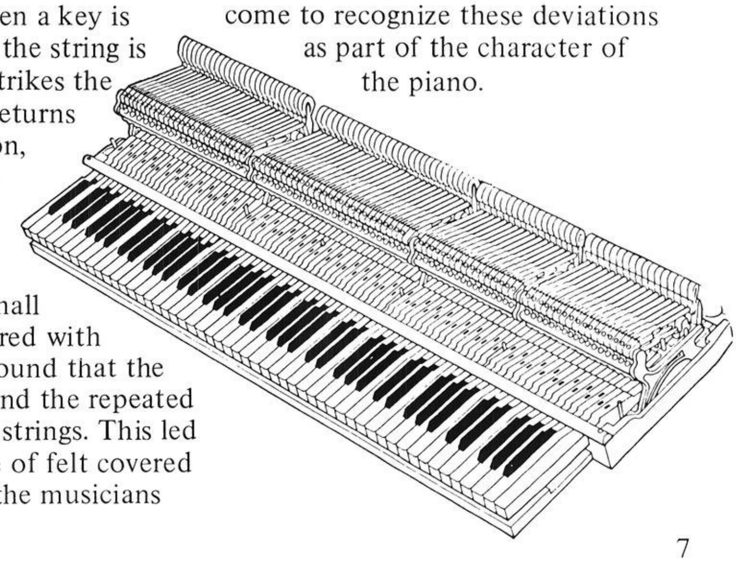
Another feature that causes deviation between the ideal and the real piano is the hammer action involved in displacing the string and setting up vibration. Christofori developed the original upward striking hammer in the early 18th century. His design took advantage of the downward force of gravity to return the hammer to its original position. Most modern 'action' is modeled after Christofori's. A present day piano's action can contain more than 7000 parts. When a key is struck, a damper on the string is lifted, the hammer strikes the string, the hammer returns to its original position, and the damper falls to damp out the vibration.

In early pianos the hammers were small blocks of wood covered with soft leather. It was found that the leather could not stand the repeated stress of striking the strings. This led eventually to the use of felt covered hammers. Felt gave the musicians the ability to 'voice' their pianos. If the felt on a hammer is too hard it produces a harsh tone. Instead of replacing a key, a pin can be used to prick the felt and loosen it so the hammer will produce a mellower tone. To increase the brilliance of a tone, the felt can be filed down and made harder on the striking surface.

Many of the latest advances in piano design originated from efforts to reduce the mechanical sound caused by the hammer action. The impact noise of hammer against string is very noticeable in the upper octaves, where it can be almost as loud as the tone produced. Not much can be done to reduce that noise. Felt and other dampers are used to keep the hammer from banging as it returns to its position after striking. Springs are used to remove the hammer from the string as soon as it is struck, as well as to slow the speed at which the hammer falls back into place.

While piano designers try to find ways to minimize the mechanical noise of the action, some piano composers use this quality to their advantage. An American composer, Edward MacDowell, in his Piano Concerto No. 2 indicates certain passages are to be played martellato, that is, to be played with as much hammer noise as possible.

Pure acoustical theory is fine for the physicist but the limits of the material world will always cause deviation from theory. These deviant characteristics in sound have been part of the piano since its invention. Composers and listeners alike have come to recognize these deviations as part of the character of the piano.



# The fine arts

## An achievement in acoustics

by Bob Polasek

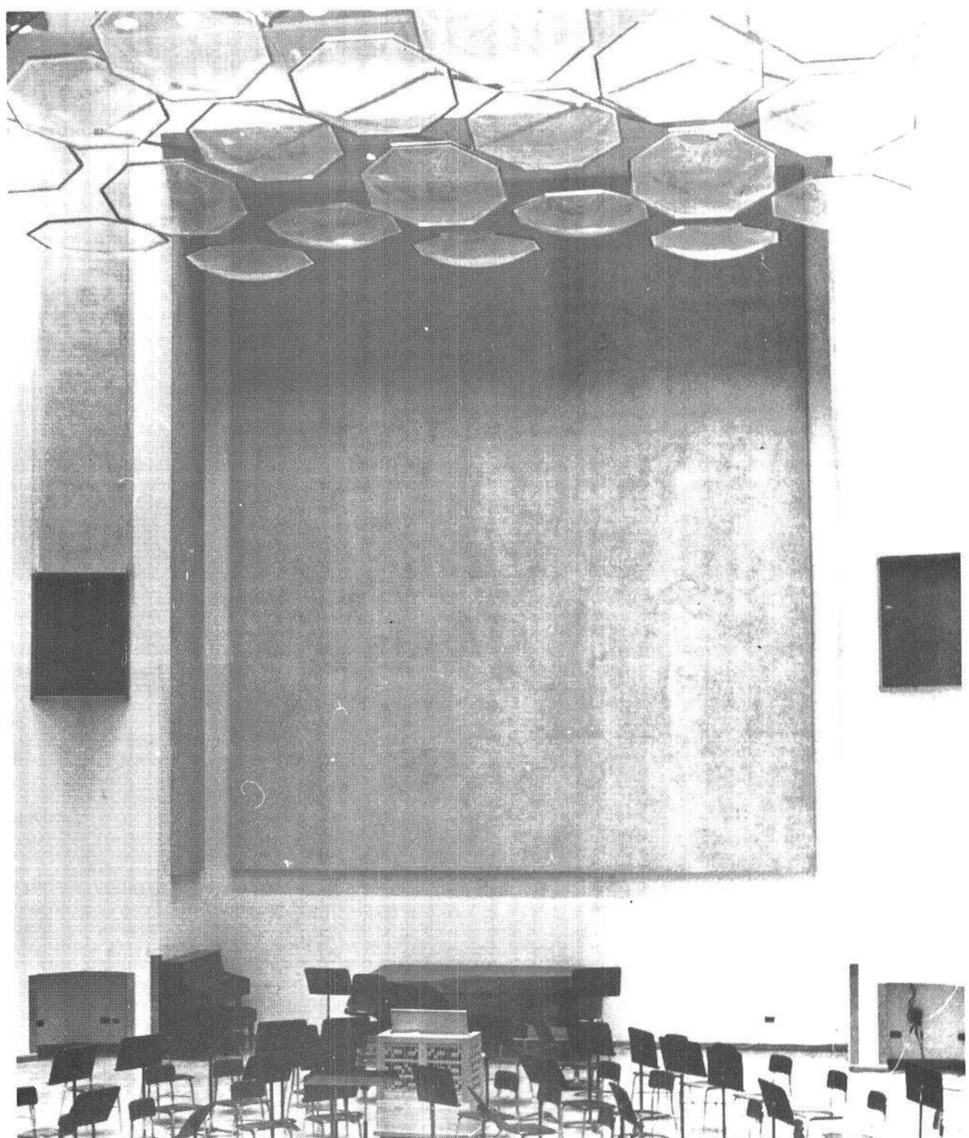
*The acoustic design of concert halls and athletic auditoriums is a science studied by many top sound engineers. Since modern facilities are being built to serve a number of purposes with a limited budget, the dimension of economic practicality has entered into the design and construction. This article outlines the basic principles of acoustic engineering and indicates how acoustic design firms, such as Bolt Beranek and Newman, Inc., have applied the basics of quality sound in the design of various facilities in Wisconsin.*

Constructing the perfect acoustic system is the ultimate goal of all sound engineers and technicians. With the days of the old opera house virtually gone (i.e., the smaller theaters which were built for one specific purpose), acoustic design specialists have inherited the problem of constructing facilities which accommodate a variety of performances, seat large crowds, and meet cost efficient budgets. Although near perfection in acoustic design has been achieved, some compromise must be made in the sound system to insure that the facility meets all of its requirements.

The Milwaukee Center for Performing Arts, acoustically designed in 1969 by Harry Weese and Associates (a subsidiary of Bolt Beranek and Newman, Inc.) is a cultural civic center for Milwaukee's Ballet, Repertory, and Opera Companies; the famous Milwaukee Symphony; and many visiting artists. Scenically located on the banks of the Milwaukee River, the Performing Arts Center has attracted many top artists to perform in Milwaukee. The PAC consists of three concert halls: the Wehr Drama Theater, Vogel Recital Hall, and multi-purpose Uihlein Hall.

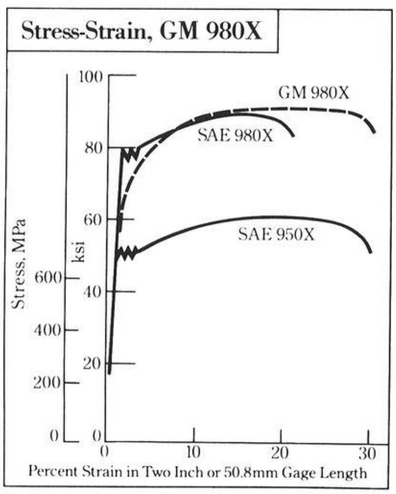
The acoustical elements of Uihlein Hall, the 2500 seat central facility designed after the Boston Symphony Hall, were incorporated into a patterned design which augments the beauty of the hall. These elements were originally designed and tested from a model ten times smaller than the size of the hall. The stage shell and plastic, sound-reflective canopy have enabled musicians to hear one another, adding to the intimacy and clarity of the woodwinds and strings while prohibiting brass and percussion sections from overpowering these finer sounds. Acoustic panels are adjustable at the touch of a button. A loudspeaker cluster along with additional sound panels are available for further amplification. The ceiling and walls of

*continued on page 12*

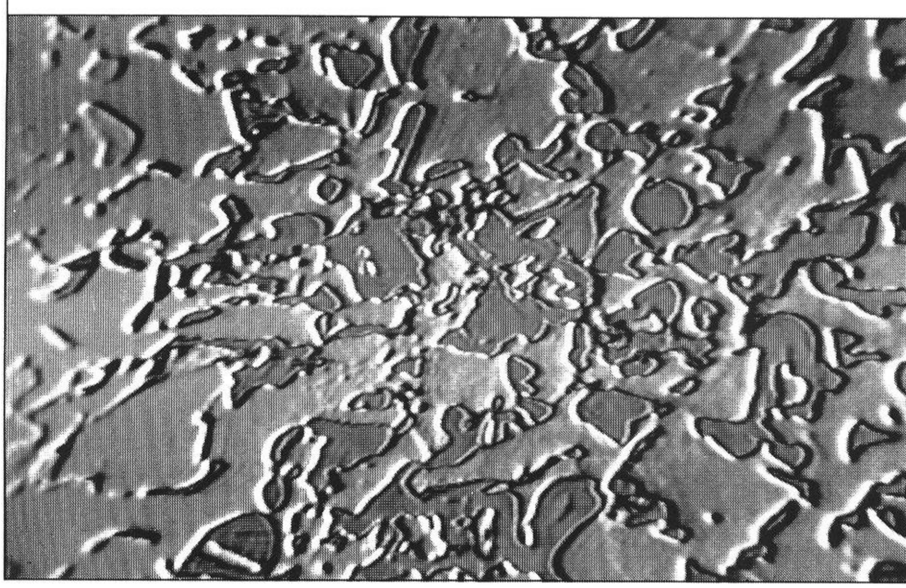


# The Ductility Factor

*The use of high strength, low alloy steel has been severely limited, due to its low ductility. Now, a simple heat treating and controlled cooling process, developed at the General Motors Research Laboratories, has successfully enhanced formability properties without sacrificing strength.*




*A comparison of the stress-strain behavior of GM 980X, SAE 980X, and SAE 950X steels. GM 980X offers greater ductility at the same strength as SAE 980X, and greater strength at the same ductility as SAE 950X.*



*Scanning electron microscope micrograph of dual phase steel at a magnification of 2,000. The matrix (background) is ferrite; the second phase is martensite.*

FOR SOME TIME, automotive engineers and designers have been faced with the challenge of building cars light enough to get good gas mileage, but still roomy enough to comfortably transport four or five passengers. One technique which has proved fruitful is materials substitution.

Lighter materials, such as aluminum alloys and plastics and high strength, low alloy steels (HSLA), are being phased into new vehicle designs to replace certain plain carbon steel components. Each, though, has displayed inherent problems which limit its utilization.

Unlike plastics and aluminum, however, HSLA steels have the same density as plain carbon steel. Weight reduction is achieved because thinner sections (less volume) can be used to carry the same load. Since the formability (ductility) of most high strength steels is poor, though, it has only been possible to form simple shapes from it. This has severely limited the widespread use of HSLA steels (such as SAE 980X) for auto components. New hope for the increased utilization of HSLA steel has arisen, however, with the development of a new dual-phase steel, GM 980X, at the General Motors Research Laboratories.

General Motors is not in the steel business, and GM 980X is not a brand of steel. GM 980X is the designation for a type of steel displaying mechanical properties similar to those of the samples first formulated at the General Motors Research Laboratories. "GM" in the designation indicates that the steel is a variation of the conventional SAE 980X grade. In the standard SAE system for material identification, "9" designates that the steel is HSLA. "80" is the nominal yield strength of the metal in thousands of pounds per square inch. The "X" denotes a micro-alloyed steel—one containing on the order of 0.1% of other metals such as vanadium, columbium, titanium, or zirconium as a strengthening agent.

GM 980X displays the same strength, after strain hardening, as SAE 980X steel, but has far more ductility. This characteristic allows it to be formed into various complex shapes which were previously thought to be impossible with HSLA steels. The superior formability of GM 980X has substantially increased the utilization of HSLA steel in the manufacturing of automotive components such as wheel discs and rims, bumper face bars and reinforcements, control arms, and steering coupling reinforcements.

Dr. M.S. Rashid, discoverer of

the technique to make GM 980X steel, comments, "I was working on another project using HSLA steel, when I noticed that if SAE 980X steel is heated above its eutectoid temperature (the temperature at which the crystalline structure of metal is transformed) for a few minutes, and cooled under controlled conditions, the steel developed significantly higher ductility and strain-hardening characteristics, with no reduction in tensile strength."

FURTHER experiments proved that the key variables to make GM 980X are steel chemistry, heating time and temperature, and the rate at which the steel is cooled. Specimens of SAE 980X were heated in a neutral salt bath, then cooled to room temperature with cooling rates ranging from 5° to 14°C/sec. (9° to 26°F/sec.). Dr. Rashid notes, "We found that the maximum total elongation resulted when the cooling rate was 9°C/sec. (16°F), and the lowest total elongation resulted from the highest cooling rate (14°C or 26°F/sec.)."

GM 980X steel has a high strain-hardening coefficient or n value, accompanied by a large total elongation. The n value gives a measure of the ability of the metal to distribute strain. The higher the n value, the more uniform the strain distribution and the greater the resistance of the metal to necking (localized hour-glass-shaped thinning that stretched metals display just prior to breaking). Tests have proved that GM 980X distributes strain more uniformly than SAE 980X, has a greater resistance to necking, and thus has far superior formability.

"The superior formability of GM 980X compared to SAE 980X steel appears to depend on the nature of two microstructural constituents, a ferrite matrix (the principal microstructural component) with a very high strain-hardening coefficient, and a deformable martensite (the other crystalline structure) phase. In the SAE 980X, failure occurs after the ferrite becomes highly strained, but when the GM 980X ferrite is highly strained, strain is apparently transferred to the martensite phase, and it also deforms.

"Therefore, voids leading to failure do not form until after more extensive deformation has occurred and the martensite phase is also highly strained. Obviously, the exact nature of these constituents must be important, and any variations in the nature of these constituents could influence formability. This is the subject of ongoing research."

Dr. Rashid's discovery represents a significant breakthrough in the area of steel development. His findings have opened the door to a new class of materials and have completely disproved the commonly held belief that high strength steel is not a practical material for extensive automotive application. "At GM, we've done what was previously thought to be impossible," says Dr. Rashid, "and now we're hard at work to find an even stronger and more ductile steel to meet the needs of the future."

## THE MAN BEHIND THE WORK

M.S. Rashid is a Senior Research Engineer in the Metallurgy Department at the General Motors Research Laboratories. He was born in the city of Vellore in Tamil Nadu (Madras), India, and attended the College of Engineering at the University of Madras—Guindy. He came to the United States in 1963 and was awarded a Ph.D. in Metallurgical Engineering from the University of Illinois at Urbana-Champaign in 1969. After a three year Post-Doctoral Fellowship at Iowa State University, he joined the staff of the General Motors Research Laboratories.

Dr. Rashid is continuing his investigations into the development of even more ductile high strength, low alloy steels. When not in the lab, he enjoys relaxing by playing tennis and racketball with his wife, Kulsum.

Uihlein Hall are made of straw-colored ornamental plaster with golden accents. The surfaces have been shaped and oriented to bring rich, full sound to the listener from the proper directions and in the correct amounts. The stage is of adjustable size—larger for symphony performances—with a demountable orchestra shell which blends into the scenery when not in use. A priceless chandelier of gold and glass also compliments the beauty of Uihlein Hall.

The Wehr Theater seats over 500 spectators around a thrust stage and contains all of the features found in a fine theatrical facility. Two basic acoustical problems with the thrust stage are: (1) the prevention of noise interference from mechanical systems and adjacent rooms with vocal sound quality and (2) providing a virtually "dead" acoustical environment (low reverberation time) which allows clear separation of voice projection without quieting the sound to the extent that the hall is unresponsive to their voices. Bolt Beranek and Newman, Inc., carefully shaped the hard surfaces to reinforce the actors' voices and muffled the surfaces which could not contribute positively to the sound quality. Upholstered seating, carpeting and glass fiber near the lighting grid are the only sound absorptive materials required in the room.

Vogel hall, the smallest of the three PAC concert halls (seating approximately 500), is used both as a symphony rehearsal hall and a recital hall. The side walls are covered with velour panels for sound dampening effects. Stage walls are tilted forward to reflect sound back toward the musicians. Oak parquet beneath the seats combine with the hard reflective surface of the plaster balcony ceiling structure to provide a short reverberation time for high sound articulation.

In early March of 1980, Dr. Theodore Schulz, BBN's Director of Technical Acoustics and distinguished winner of the 1976 Silver Medal in Architectural Acoustics, performed a series of renovations at Uihlein Hall. The work consisted of replacing a series of panels, originally designed for sculptural purposes, with a set of six and one-quarter by five foot sound contoured panels. The recent improvements have made Milwaukee's Performing Arts Center one of the top acoustical structures in the nation.

Last month's grand opening of the Madison Civic Center was well received by those attending. Highlights of the opening month included: the Duke Ellington Orchestra, the San Francisco Ballet, the Milwaukee Symphony, and "Showboat". The Civic Center consists of the 2200 seat Oscar Mayer Theater and the Isthmus Playhouse, both possessing excellent acoustic quality.

The University of Wisconsin's Mills Hall was recognized as Madison's foremost civic center until just recently. Mills Hall, also acoustically designed by Henry Weese of BBN in 1973, hosts concert and recital performances in the U.W.'s Vilas Hall.

The main characteristic of a perfect acoustic design is equal reverberation time, meaning that one second of actual sound will reverberate for exactly one second throughout all parts of a facility. While acoustic engineers of concert halls strive to achieve this perfection, the design of athletic auditoriums is slightly different. The Milwaukee MECCA Sports Complex has a reverberation time of four to five seconds, which increases the sound by a factor of five. The extra sound, which is directed from all angles toward the center of the floor, increases the "home court advantage" that the crowd gives to the home team. The MECCA Sports Complex, one of three multi-purpose convention and exposition facilities located in downtown Milwaukee, is home for the NBA's Milwaukee Bucks, hockey's Milwaukee Admirals, and many special events.

During the design of an acoustic system, the technicians must consider the sound generation, propagation, perception and interaction with building materials. Designing an enclosed acoustical system requires the technician to solve the problems of sound reflection and ideal reverberation time to conform the sound quality to each individual facility.

The law of specular reflection, a law which relates the angles of sound wave reflections from plane surfaces by stating that the angle of reflection equals the angle of incidence and that the two angles are coplanar with the surface normal, is a fundamental principle in acoustic design. Sound panels (or baffles) are situated near the ceiling and walls for the purpose of reflecting sound. The size, shape and surface texture of the sound panels depend on the desired sound effects. Sound panel surfaces are of three basic types: convex, concave, and flat. Convex panels, which direct and amplify sound waves from many directions toward the center of the room, are popular in the design of athletic auditoriums. Conversely, concert hall designers prefer the flat baffles, which evenly distribute the sound throughout the room. Sound panel reflection variables, such as surface area and degree of smoothness, control the amount of projected sound. Smoother sound panels with larger surface area project a greater percentage of the original sound at a sharper angle. The wavelength of the sound is also an important parameter in acoustic design. A shorter wave frequency increases the accuracy and intensity of the reflected sound waves. Sound not reflected, either due to insufficient baffle surface area or smoothness, is refracted toward the ceiling and lost. Corner reflection panels are installed where two walls and the ceiling meet at a perpendicular. These panels reflect sound back toward its original direction. The acoustic systems in many modern buildings are adjustable, allowing for sound panel alteration which will suit the variety of sound patterns encountered in many types of performances.

The reverberation time of an enclosed facility is a measure of sound level over a period of time. The sound performs a series of multiple reflections throughout a room before being absorbed by materials such as drapery, carpeting and spectators. In a room without such absorbing materials where the sound is unable to escape, the sound level increases at a rate equal to the increase in original sound or it remains constant if no sound is added. The reverberation time is quantitatively defined as the amount of time necessary for the sound to reach an intensity of $10^{-6}$ of its original level. Reverberation time also depends on the frequency of the original sound and the absorption coefficients of various materials in the building. Sound panels made of glass, stone and finely polished wood absorb very little sound, whereas plywood, felt or fiber baffles absorb a great deal of sound. Acoustic engineers must combine the proper materials to create the desired sound intensity and balance in a hall. During this design, the technicians take into account the fact that the reverberation time is directly proportional to the time required for sound to decay.

Equilibrium sound, or the maximum sound level obtainable at a given power level, is also directly proportional to reverberation time, meaning that longer reverberation time hinders the sound in reaching its maximum level throughout a room. The equilibrium sound is quantified as the power of the sound source divided by the area of the room's absorption material. In addition longer reverberation time increases the intensity of the equilibrium sound level, which is often desired in athletic facilities. In order to keep this equilibrium quantity at a desirable level, reverberation time and the power of the sound source must be increased as the area of the auditorium increases. Reverberation time is also frequency dependent, with lower sound frequency requiring a longer reverberation time.

As is the case with acoustic variables, such as sound panel material, surface texture and angular arrangement, the reverberation time must be adjusted to accommodate the auditorium's requirements. The additional sound absorption caused by a full house of spectators must also be considered when the acoustical variables are adjusted.

Bolt Beranek and Newman, Inc. is one company which specializes in acoustics and environmental technology. They consult on all types of acoustics—sound, noise, shock, vibration and ultrasonics.

Industrial and business noise level requirements set by OSHA (Occupational Safety and Health Act) have expanded BBN's involvement in sound reduction projects, which have eliminated noise pollution in places such as industrial plants and offices, airports and freeways. Acoustical measurement devices, such as miniature accelerometers used for shock and vibration measurement with built-in preamplifiers sensitive over a wide frequency range, and portable sound monitors measure, calculate and print out these sound levels..

BBN is most notably famous for their design and renovation work with acoustical facilities. BBN sound technicians have combined their ingenuity with architects, engineers, and building owners in the construction of concert halls, offices, sports arenas and stadiums, hospitals, schools, and residential facilities. The company has enhanced sound quality for musical and dramatic effects; designed sound reproduction systems; and developed lighting, audiovisual, and stage orientation machinery for many theaters and performing arts centers.

The quality of sound projection in many different types of facilities has greatly improved in recent years. New structures possessing highly impressive acoustic and architectural characteristics are being designed and built in cities throughout the world. Acoustic engineering consultants such as Bolt Beranek and Newman, Inc., have contributed substantially to this progress.

# La French horn

by Mike Engh

*Mike Engh is a graduate student in the Department of Electrical and Computer Engineering. He has played the French horn for 11 years and is currently a member of the UW Horn Choir.*

The acoustical characteristics of the modern French horn make it one of the most tonally colorful instruments of the contemporary orchestra, and one of the most difficult to play. The name French horn is a misnomer. The horn as we now know it has evolved from the German ideal of horn tonal color: dark, mellow, deep, rich, smooth, broad. The French school horns, on the other hand, were smaller and were characterized by a small, thin, bright open tone. The most common horn is built in the key of F, meaning its range of resonant frequencies correspond to notes of the F scale on the piano.

The horn is held upright by the left hand with the bell facing backwards. The right hand is slightly cupped and placed inside the bell partially occluding the opening. A tone is produced by forcing a steady stream of air through almost closed lips pulled taut by muscles in the corners of the mouth and pressed gently against the mouthpiece. The lips are alternately forced open and snapped shut producing a waveform of sharp pulses rich in overtones. The shape the lips assume inside the mouthpiece is remarkably like the shape of the double reeds of the oboe and bassoon. The quality of the sound produced is affected by four factors: the embouchure (the shape and use of the muscles of the mouth); the material of which the horn is constructed (usually an alloy of copper and zinc known as brass, or of copper, zinc, and nickel, known as nickel silver); the shape, width, and length of the tubing, bell, and mouthpiece; and the placement and shape of the hand in the bell.

The length of tubing of the F horn is about 3.7 meters creating a fundamental frequency of about 43.6 Hz. Because the mouthpiece is small and the horn has a long and narrow bore, the fundamental is rarely used and is in fact unattainable by many horn players. By increasing the tension on the lips the horn can sound frequencies of integer multiples of the fundamental due to different resonant modes of vibration. For an open, cylindrical tube these frequencies are given by:

$$f = n\frac{v}{2L}$$

v: speed of the wave
n: an integer $> 0$
L: length of the tubing

The best range of notes for the horn is from the fourth to the twelfth harmonic (F3 to C5 on the piano) whereas the best range for the trumpet is from the first to the eighth harmonic. Above the seventh harmonic the attainable frequencies are a whole step (half as dense as notes on the piano) or less apart. This means the player has to know precisely the sound of the note he is about to play and set his lips accordingly for the correct frequency to be selected. The fact that the frequencies are so close over most of the useful horn range is the main reason horn players are constantly plagued with 'busted' notes.

The expression for the resonant frequencies of the horn is complicated by the fact that the horn is approximately conical in shape with its narrowest point at the mouthpiece. It has intermittent cylindrical lengths for the tuning slides and valve connections, and a wide flaring bell, parts of which can be approximated by the expression:

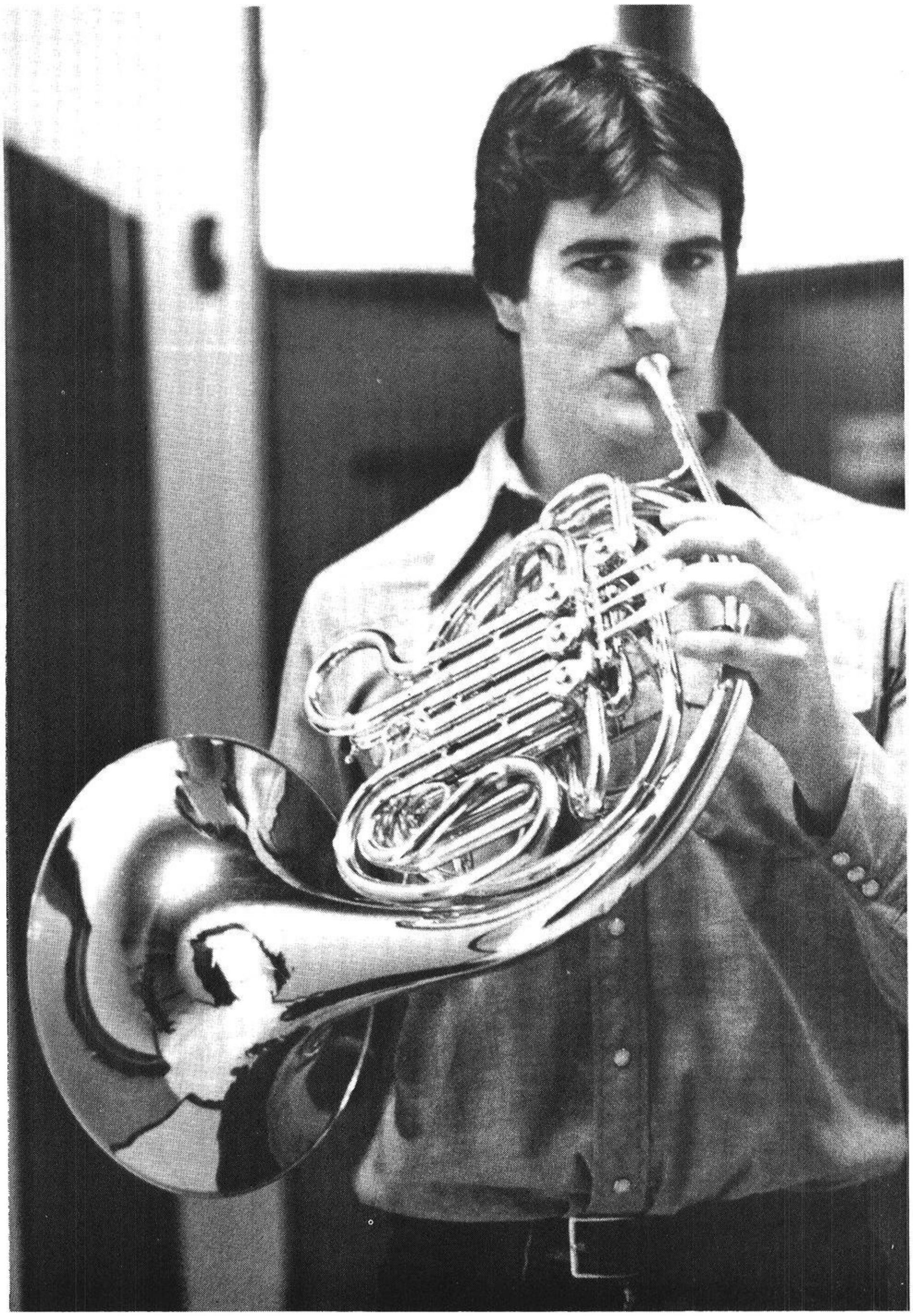
$$xt = \frac{x}{y^n}$$

xy: the size of the bore at a distance Y from the bell mouth.
x: the bell mouth diameter (typical 27-33cm).
n: the flare constant (typical .8 cm).

The shape of the bell is designed to radiate sound energy more efficiently than a simple conical shape. The bell also produces stronger higher harmonics yielding a richer, more colorful tone.

The acoustic length of the horn is about 3.9 meters because a resonant antinode is formed slightly beyond the end of an open tube. This length is increased if the end is narrow or obstructed and is frequency dependent. By occluding the bell opening the right hand serves two purposes: it increases the acoustic length thereby lowering the pitch, and it decreases the intensity of the upper partials because their acoustic lengths are increased disproportionately with the fundamental. This forces the partials to be out of tune with the fundamental, and they are thus less easily excited.

An interesting phenomenon called "stopping" occurs when the hand is placed across the throat of the bell, obstructing it completely. In this case the pitch is raised by about one half step because the hand



cuts off the end portion of the bell, decreasing the acoustic length. Stopped notes sound distant when played softly? they sound piercing, cutting, and strident when played forcefully.

The valve system was added to enable the horn to play in keys other than F. The keys rotate a cylinder in the valve casing which adds a fixed length to the horn, lowering the pitch. For example, the center key lowers the horn one-half step; the first valve, one whole step; and the third, 1.5 steps. By various combinations of the valves, all of the steps between an open tone (no valves) and 3 steps below it can be played. This system, however, is not quite as simple as it sounds. The second valve tubing length is of a fixed ratio to the length of the open horn. Therefore it is not long enough to lower the horn with the third valve down an entire one-half step. So the 2.3 valve combination is sharp, not quite 2 steps lower. The problem is greater for other combinations and greater still when all three valves are used.

There are various ways of tuning the valve slides so the errors are more evenly distributed over all note combinations. If the error is small enough, a player with a good ear and strong embouchure can "lip" the pitch up or down to adjust the notes to blend with the rest of the orchestra. With a strong embouchure the resonant frequency can be forced slightly higher or lower. Blues trumpet players are famous for this effect. One must be careful not to bend the pitch too far and jump accidentally to an adjacent harmonic, especially in the higher ranges.

In the lower ranges where the harmonics are farther than 3 steps apart, there are notes that cannot be played with the standard 3-valved F horn. It has become commonplace to incorporate a fourth valve which shifts the key of the entire instrument to B-flat, pitched an interval of a fourth higher. This double horn arrangement enables all of the chromatic tones (half steps) to be played over the entire range of the instrument. When using the B-flat side in the upper register, the resonant frequencies are farther apart, allowing the player to be more confident of hitting the right note. Many of the notes overlap between the F and B-flat sides, requiring the horn player to learn many sets of fingerings for each note.

The scale of notes in which the frequencies are the ratio of small integers is called the diatonic scale and is followed by the notes of the horn. This limits the instrument to one key because another key would have oddly proportioned intervals. The even tempered scale enables the piano to play in any key, but forces the horn player to adjust the natural notes of the horn to the even tempered scale by "lipping."

If after this discussion you remain unconvinced that horn playing and physics make a good mix, I suggest you talk to Charles Kanalovski. He has been first horn of the Boston Symphony for five years. In addition to this honor he also holds the distinction of having a Ph.D. in experimental nuclear physics.

# Music and engineering

by Mike Zambrowicz

The University of Wisconsin–Madison School of Music and College of Engineering are two academic areas which are seldom, if ever, mentioned in the same breath. Besides being located on opposite ends of the campus, they represent two traditionally different types of study. On one hand there is music which tends to be creative, artistic, and beautiful, while on the other there is engineering which can be creative, but is also calculated and practical. Yet these two schools have a number of underlying associations as discussed by Prof. Dale Gilbert, Director of the University of Wisconsin's School of Music.

The University of Wisconsin attracts some of the most successful high school students from Wisconsin and around the nation, many of whom have had prior musical experience. The School of Music offers these students the means to further their musical experience, whether they are pursuing music or some other field as their major field of study .

For example, the University of Wisconsin Marching Band, under the direction of Michael Leckrone, besides being considered one of the nation's finest, recruits a good percentage of its members from the College of Engineering. There are also a number of engineering students enrolled in many music appreciation courses which are offered each semester.

It is Prof. Gilbert's belief that many engineers are attracted to music because the "engineering mind" holds a fascination for music. Music is the organization of sound, and the principles of putting sound together prove to be interesting to many engineering students. In this way the engineer can apply his knowledge to something he enjoys—music.

The School of Music offers courses for non majors in the areas of music appreciation and music theory. Students enrolled in these courses find them informative, enjoyable and somewhat relaxing; a welcome change of pace from their engineering, math or science courses.

Besides catering to the needs and interests of the non-majors, the School of Music has about 450 music majors of its own. Prospective music major candidates must audition one year prior to entering the UW. Only about 35 of approximately 120 people auditioned each year are accepted. The School of Music offers courses leading to the B.A., M.A., Ph.D., and Doctor of Musical Arts degrees in areas such as music theory, history, performance, and composition.

The Department also participates in a demanding concert schedule; about 270 concerts each year featuring the bands (Symphonic, University, Concert, Jazz and Marching/Varsity), orchestras, choruses and student recitals. These performances are held at various locations both on and off campus. The Humanities Building, besides being occupied by the School of Music, also has several performance halls used by the students and faculty of the school. One of these is the Eastman Organ Recital Hall which houses a 51-rank organ and serves as an auditorium for student recitals, holding up to 180 persons. The Morphy Recital Hall also seats up to 180 and is used both for recitals and classes. The main performance hall for the School of Music is the Mills Auditorium which has a seating capacity of 775. It is used for concerts and for some classes.

Across the street from the Humanities Building at the base of Bascom Hill is the old Music Hall which serves as the main performance center for the annual opera production of the School of Music and the Drama Department.

Perhaps the most visible and publicized school performance centers are the Dane County Coliseum, the Field House, and Camp Randall Stadium where season after season the UW's Marching and Varsity Bands continue to enthusiastically entertain and boost the spirits of the many thousands of cheering Wisconsin Badger fans. The bands also make occasional performances at professional and collegiate athletic events.

Lest we forget, northwest of Bascom Hall and in front of the Social Sciences Building stands a lone stone tower which often goes unnoticed and yet musically is as much a fixture of this campus as is the Humanities Building. The University of Wisconsin Carillon, under the direction of Prof. John Harvey, has tolled its melodies consistently to students within hearing distance for the past 45 years. The Carillon has a playing clavier and 56 bells with a range of four and a half octaves. It plays programmed melodies much like an old-fashioned player piano, but it can also be played by someone skilled in its use. Carillon concerts are given on Sunday afternoons from May through December.

# Creating the concert hall environment

by Tom Van Sistine

Why doesn't the recorded performance of a concert, played on a good sound system in your home, sound as good as a live performance at a concert hall? Part of the problem does occur in the recording process, but most of the live effect is lost because of differences in the listening environment. Let's look into what determines these differences and ways to overcome problems.

When listening to someone speak or sing in an auditorium, we hear the primary sound as it comes directly to us, along with the secondary reflected sounds which come shortly thereafter. The delay occurs because the sound travels first to a wall, where some of it is absorbed; the rest bounces off and finally reaches our ears. The extra distance the sound has to travel causes a delay of up to a few milliseconds (1ms = 1/1000sec). Because there are at least four walls, a floor, and a ceiling, there are multiply reflected sounds. Secondary sounds are much more subtle than primary because of the absorption. In a small room, secondary reflections will have little delay and may be indistinguishable from the primary one. Another factor of the listening environment or "ambience," is the material used in construction, as well as the number of people in the room. A small room filled with carpeting, drapes, and a couch, or even a suspended ceiling has a degrading effect. Materials like these absorb sounds, resulting in a flat, lifeless response.

Before remodeling your house for your stereo or just doing without one, you should know that good old American ingenuity has come up with a way to produce the ambience of a concert hall with electronic technology. The first thing necessary to do this is to provide some way to delay a primary signal for a few milliseconds. This will give us a secondary echo.

A first generation analog delay device was mechanical and consisted of a spring and two transducers. The primary signal was driven into one end of the spring by a transducer, and the signal traveled relatively slowly through the spring to the other end, where it was converted back to a signal and amplified. Drawbacks to these early delay devices were that the delay was fixed by the length of the spring, and that they produced a "tinny" sound. Second generation analog delays used so-called "bucket-brigade" devices. These are named after the process firemen previously used to transport water from one place to another. Forming a line, they passed buckets of water from one end to the other. Similarly a signal, in the form of a voltage, can be padded down by means of transistors and capacitors. The time it takes to go through the device is the amount of delay in the signal. To change the length of delay, one can either lengthen the path by adding several devices or change the rate of speed at which the signal travels through the device. This second generation delay is used in many of today's commercial units.

A newer approach is the digital method. This uses computer-technology. The primary signal is changed by an analog-to-digital converter to a binary number. Then it can be sent through a shift register, which works something like the bucket-brigade, or it can be placed in a memory bank for the length of delay necessary. After that it is converted back to the signal, by a digital-to-analog converter. The advantage of digital over analog delay is usually the improved signal-to-noise ratio. Most commercial units are designed to suppress noise, and either analog or digital delays can be used.

So far we have only a single echo. To provide the many reflections normally associated with a room, we must recirculate this first echo over and over until it fades. With stereo equipment there are two delay paths and the signals are often cross-connected to blend them together in a natural manner.

All this may sound quite sophisticated and difficult to set up. This is not necessarily so. A reverberation unit, or ambience generator, plugs into an auxiliary output and has its own power amplifier and set of speakers. When a reverberation unit is used along with your stereo, the volume should be just high enough to blend in the background and not stand out. If the reverb is turned off, the music will sound quite flat in contrast.

During operation, adjustments must be made for each record. For example, a recording of a live concert would have a bit of ambience recorded in it, and to add more would muddle the sound. However for records produced in a studio, the response is often much flatter, and extra ambience would greatly enhance the sound.

Time delay devices can also be

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# A song in the heavens

by Russell Poeppel

Did you ever consider the idea that the planets sing? If you're like most people, you probably haven't. In Pythagoras' time the planets were believed to have spherical orbits. Pythagoras reasoned that since each planet has a distinct velocity as it moves in its orbit, a characteristic note would be produced. Further, the combination of the individual notes for all the planets would create a single eternal chord audible only to the divine ear.

In 1619 Johannes Kepler published "Harmonicas Mundel" (Harmony of the Universe) in which he extended Pythagoras' theory as a result of his discovery that the planets move in elliptical, rather than spherical orbits. From this he reasoned that the planets do not produce a single chord, but an ever changing combination of chords which blend together to form one harmonious master symphony.

Recently, with modern technology, it has become possible to produce an audible replica of this symphony. This has been accomplished by Willie Ruft, associate professor of music and John Rodgers Silliman, professor of geology; both of Yale. Their method follows.

The change in pitch of a revolving object is a function of its angular velocity. Imagine that a rubber ball attached to a string is spun over your head. As the ball is spun a tone is produced with a frequency which increases in a smooth flowing way as its velocity is increased. These smooth changes in tone are called glissandos.

Glissandos of this type are impossible to produce by a synthesizer or any keyboard instrument because they are not formed by discrete notes. A horn could produce a flowing sound change but does not have the correct harmonies. Furthermore, nine separate changing tone clusters (one for each planet) must be put together in the proper sequence.

The elliptical nature of the planets' orbits causes the glissando formation. As the planet nears the sun its velocity is increased, resulting in an equivalent increase in pitch. As a planet moves away from the sun, its velocity and therefore its pitch decreases. To determine the pitch changes, accurate formulas had to be worked out for the actual movement of the planets.

Another difficulty encountered with producing the replica occurred when it was found that the tone of the outer three planets were too low to be audible to the human ear. This was solved by making the outer three planets audible as beat frequencies. A beat frequency is a low beating sound like that of a drum or a metronome produced when low frequencies interact. These beat frequencies added a rhythm section to the symphony.

All of this information was then programmed into a computer at Princeton University by computer specialist Mark Rosenberg. The final product is the album "Harmony of the World" which contains 264 years of planetary history. It appropriately starts on December 27, 1571, Kepler's birthdate.

The album is a grand symphony based on a scale of five seconds per year. Mercury, the fastest and closest planet to the sun, produces a high pitched chirping sound which could be paralleled to the cry of a killdeer. Mars, having the most eccentric orbit, produces a glissando which slides up and down a wide range of notes. Jupiter produces a majestic organlike tone which shifts slowly and weaves mysteriously with Saturn's deep growl. Interestingly, the Earth and Venus share a duet in a minor key adding a gloomy effect to the symphony.

The combined effects create a unique (and) auditory experience. The listener is placed in the middle of the solar system as the planets weave and shift around. The next time you look into the skies at the seemingly stationary planets, tip your ear and imagine that they are singing to you—they really are!



*continued from page 18*

used in other areas. One use is in electric music. With delay, a single horn or stringed instrument synthesized can sound like a whole section of instruments. This is called chorusing. With special modifications, flanging and vibrato can be introduced. Some records are produced today with ambience built-in by electronic means, but the results are not as good as having your own to adjust to the needs of your own room.

A whole new dimension in sound can be realized with delay techniques. These can bring about a greater sense of natural and "live" music.

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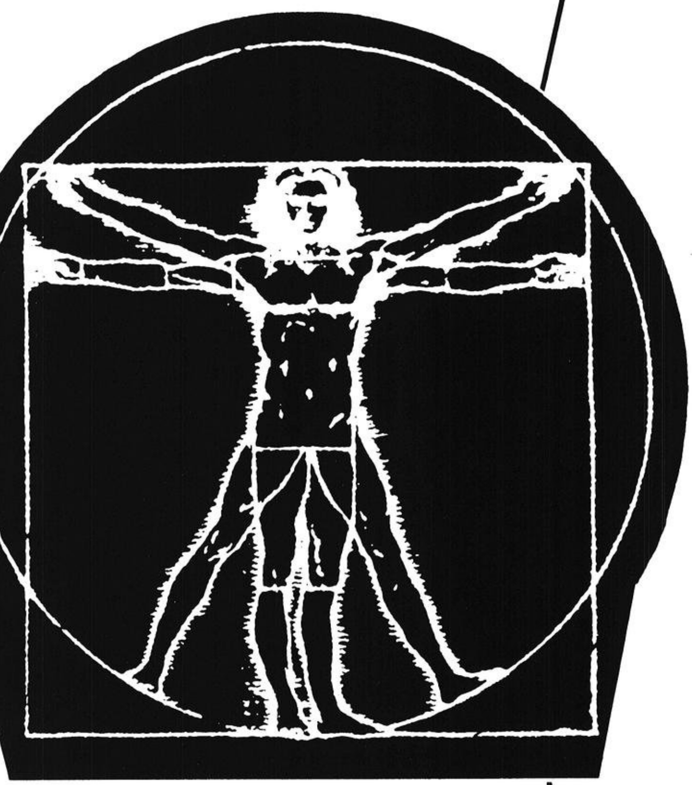

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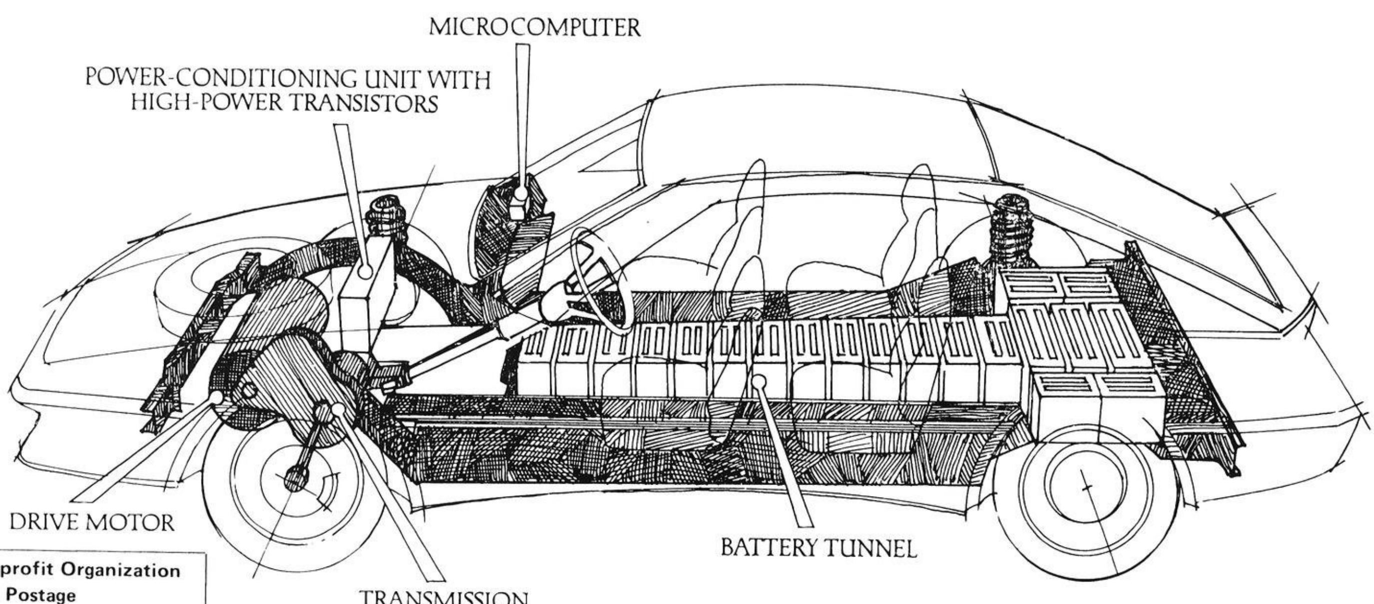


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