Improving the Acoustics in a Historic Building Using Axiomatic Design and TRIZ

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Abstract

This article investigates the use of TRIZ and Axiomatic Design to solve the problem of poor acoustics in the historic Schwab Auditorium on the Penn State University Park campus. The problem is dissected to its functional requirements and the design parameters which govern the requirements. TRIZ and Axiomatic Design are then used to create an uncoupled design which solves all the functional requirements with one design parameter each. Finally there is a suggestion on how to combine all of the solutions to solve the poor acoustic problem in Schwab Auditorium.

Keywords: Axiomatic Design, Acoustics, Physical Contradictions

1.0 Introduction and Motivation

Schwab Auditorium, a building on the Penn State University Park campus, has been around for over 100 years (Figure 1). It has been used as a classroom, as well as for stage productions, concerts and speakers. The main problem is that the current arrangement and type of speakers do not allow for the best acoustics. When the speakers are used to amplify a person's voice, the clarity of the voice is decreased. If the gain is increased, because of the spread and angle of the speakers, feedback will occur. Due to the type of speakers, the full frequency range is not increased, and higher frequencies tend to die off quicker than the lower frequencies. Because of the angle of the speakers, the balcony gets very little amplified sound, and what the balcony and back rows do receive is normally not as full as in other parts of the house (Figure 2).

The current solution is to rent speakers and place them in locations that assist the audience in enjoyable listening. This is a temporary and somewhat costly fix considering the time and effort the set up requires as well as the rental fees. Also, these speakers do not reach the sides of the balconies. This study illustrates how TRIZ methods (Savaranksy, 2000) in the context of axiomatic design (Suh, 2001) are able to be effectively used to create a permanent fix that does not cost too much, retains the historical presence of the building, while creating an enjoyable listening experience for most, if not all of the audience.

2.0 Acoustics Basics

Microphones and loudspeakers are necessary in larger spaces to allow the audience to hear everything that is being said or sung on stage. This is due to two things, first sound decays with distance by the inverse square law, second the noise floor may be too high for a person to project above due to audience noise or an orchestra. Microphones of various types are used on or near a stage to pick up vocals and transform them into electronic information. This in turn is sent to a mixer and then to the loudspeakers where it is transformed back into sound and sent out to the audience (Ahnert and Steffen, 1999).

The mixer increases the volume of certain frequencies of the sound to help make the sound more realistic and lifelike and to help carry the sound further into the audience and also force the sound to be high enough above the noise floor, or ambient room noise, so that it can be perceived by the audience. It is the difference in amplitude of sound from the noise floor that allows people to hear it; in a quiet library a whisper can be heard, but on a busy street a whisper cannot be heard. Each speaker has its own directivity, or angle from the central axis where there is no significant decrease in sound energy. This can be thought of as a cone coming from the speaker source. Depending on the frequency and volume of the sound, this cone of influence will change, and again, the sound will decay with distance. Therefore the speaker directivity, or spread, influences what group of the audience will hear the sound the best, as does the angle of the speaker box itself (Ahnert and Steffen, 1999).

Ideally there would be no sound from the speaker that would get picked up by microphones on stage; however, if sound emitted from a speaker hits a microphone on stage, feedback will occur. The electronic signal will continue to amplify itself creating a squelching noise over the loudspeakers. Ideally there would also be a certain amount of reverberation, or reflection of sound in the room, before a sound dies out. The amount of reverberation in a room determines how live (more reverberation) or dead (less reverberation) a room is. Also, the more reverberation the more difficult it can be to distinguish ordinary speech. Speakers tend to be designed to amplify speaking or singing or both. This is because speaking and singing involve different frequency ranges. Speakers that are made for speaking amplification will not amplify all frequencies of someone singing, and therefore will lead to 'muddy' sound. This muddy sound does not include the higher frequencies which add the crispness to speech. The muddier the sound, the less consonants tend to be understood by the audience, and the harder it is to understand anything said or sung on stage (HyperPhysics, 2005).

Figure 1. Schwab Auditorium (psu.edu)

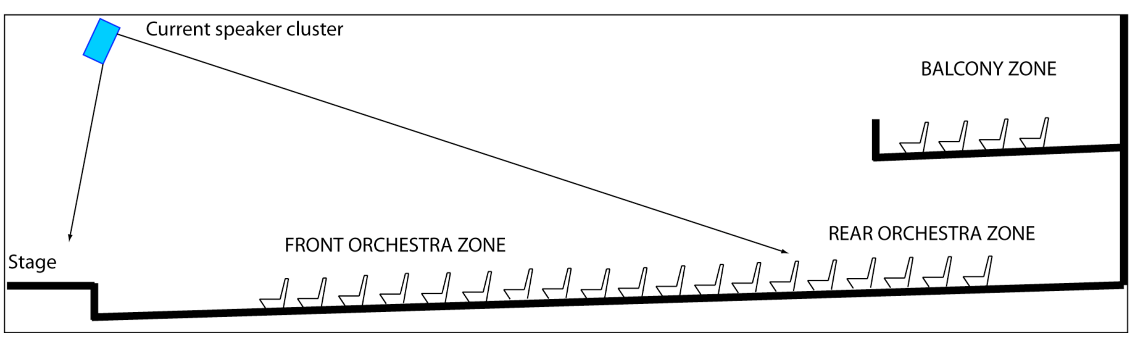


Figure 2: Schwab auditorium profile showing location of current speaker cluster

3.0 Problem Clarification with EMS Models

Energy-Material-Signal (EMS) models provide an effective means for determining the correct problem to be solved (Ogot, 2004; Ogot and Kremer, 2004). Based on black-box modeling (Pahl and Bietz, 1996) common in engineering design, EMS models functionally decompose the design problem to identify energy, material or signal flows that are harmful or insufficient.

With reference to Figure 2, let the audience be divided into three zones: the balcony, the front half of the orchestra level, and the back half of the orchestra level. In addition, the center speaker cluster is decomposed into two sets, low range and full range speakers. Figure 3 shows the EMS diagram created for the speaker system in Schwab Auditorium. In the diagram wavy flow lines indicate a harmful effect and an 'I' above a flow line indicates that the particular flow is insufficient for the desired application. The desired outcome is an improvement in sound perception of the audience: the clarity and fullness of the sound. Halfway through the house (division between the front half and the back half orchestra zones) is where the sound amplitude from the speaker drops too close to the noise floor of the auditorium for it to be effective. Included in the model are the negative effects of the low angle of the upper low frequency range speakers and the wide spread of the full range speakers: the fullness of the sound is insufficient in the balcony and the back of the house, whereas the clarity is bad everywhere due to the lack of high frequency amplification of the speakers. Also, shown in the model, due to the poor angles of the speakers themselves, the sound from the low range speakers does not affect the front of the house and the full range speakers do not direct any sound towards the balcony.

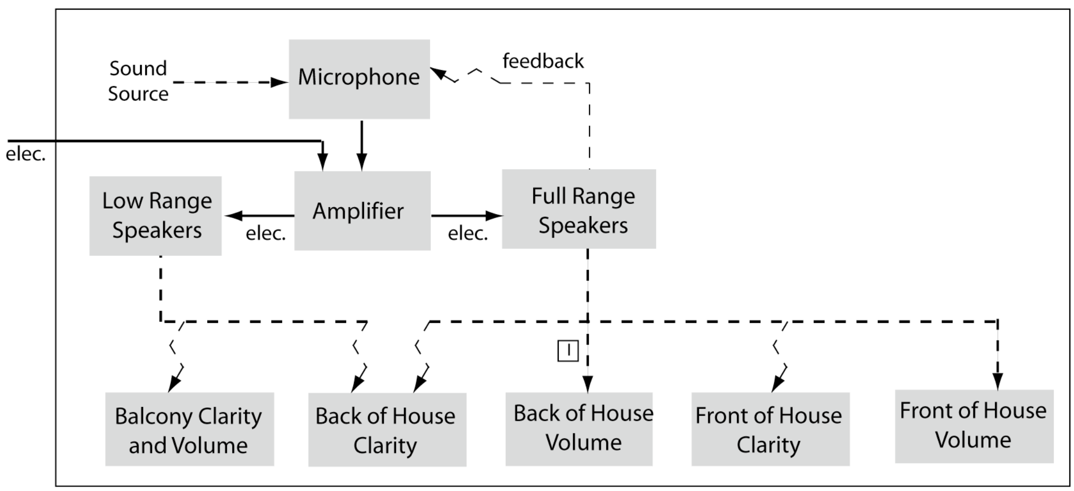


Figure 3 EMS Diagram – All flows are sound energy unless otherwise stated.

3.1 Problem Formulation with Axiomatic Design

Axiomatic design embodies two design axioms that provide guidance in moving from a bad design to a good one. The first axiom, the *independence axiom*, states that a good design maintains the independence between function requirements (FRs) and the design parameters (DPs) of the problem. The FRs are the minimum set of functional needs that fully capture the requirements of the design problem, while the DPs are the variables that describe the physical embodiment of the design that meet the FRs. The independence axiom seeks to decouple the FRs and the DPs such that a single DP controls a single FR. The second axiom, *the information axiom,* seeks to minimize the amount of information in the design – the simpler the design the better. More detail on axiomatic design can be found in Suh, (2001).

For the acoustics in Schwab auditorium, three FRs and three DPs were identified as listed in Table 1 and their initial coupling shown in Table 2. The latter is a *decoupled* design in that independence of the FRs can only be guaranteed if the DPs are solved in a particular order: DP1 ➔ DP2 ➔ DP3, for our problem. To obtain an *uncoupled* design, the ideal state according to the independence axiom, TRIZ tools were employed.

Table 1 Description of Functional Requirements and Design Parameters

Label	Description
FR1	Retain or increase the clarity of the sound for the entire house
FR2	Increase the volume of the sound for the entire house equally
FR3	Decrease the occurrences of feedback in the system
DP1	Angle of the spread of the speaker
DP2	Ratio of the distance between the furthest and closest person to the speaker
DP3	Clarity of sound from amplification system

Table 2 Decoupled Axiomatic Design

	DP1	DP2	DP3
FR1		X	X
FR2	X	X	
FR3	X		

3.2 Towards an Uncoupled Design Using TRIZ

Uncoupling the design in Table 2 was achieved in two steps: uncoupling DP1 and DP2 for FR2; uncoupling DP2 and DP3 for FR1. Description of each step follows below.

3.2.1 Separating DP1 and DP2 for FR2

The first task was to separate *DP1: angling the speaker spread* from *DP2: ratio of distances to furthest and closest person to the speaker* with respect to *FR2: increasing the volume to the entire house equally*. The speaker spread needs to hit the entire audience width-wise, but because of the spread the audience does not get the uniform volume length-wise or at the edges of the speaker's cone of influence. This can be phrased as a physical contradiction:

The spread needs to be large to encompass the entire audience, but needs to be small to minimize the variance in the speaker's cone of influence.

Separation in space can be used to find a solution for this contradiction. If we use more than one set of speakers, we can separate the signal in space. If speakers can be placed along the edges of house, maybe half way up, against the walls on the orchestra level and on the balcony level. Timing the speakers to output the signal right when the reverberation of the sound reaches that location on the wall, the speakers should amplify the sound with constructive interference; the original signal will be delayed electronically as long as it has been with distance when it is produced by the speakers, increasing the amplitude. The sound wave that leaves from the original speaker will decay with distance, and the sound wave from the additional speakers will reinforce the original sound as the sound wave passes them. These speakers can be controlled independently of the overhead cluster, so the overhead cluster is used for the front half of the audience, and the extra speakers would be used for the back half. The use of extra speakers separates DP1 (the angle) from DP2 (the distance ratio), leading to an updated decoupled axiomatic design shown in Table 3.

Table 3 Decoupled Axiomatic Design

	DP1	DP2	DP3
FR1		X	X
FR2		X	
FR3	X		

3.2.2 Separating DP2 and DP3 for FR1

The sound needs to be amplified equally for the entire audience, while not being muddied to increase the clarity for the entire house. The objective is to separate these design parameters so that FR1 (clarity for the audience) only depends on DP3 (the muddiness of the speakers) and not DP2 (the distance ratio). The addition of speakers as described in Section 3.2.2 eliminates the issue of ratio between the closest and furthest person, so that the clarity depends only on how the speakers reproduce the sound. The sound coming from the main speakers is still muddier than the sound produced on the stage. This presents another physical contradiction:

The sound has to be muddy because the current center speaker cluster does not reproduce higher frequencies involved with consonance well and they cannot be replaced, but we do not want it to be muddy as it defeats the purpose of using the speakers in the first place, allowing the audience to hear and understand what is being said on stage.

The Condensed Standards, based on the classical TRIZ 76 standard solutions, can be used to look for a general solution (Ogot, 2004). The 76 standard solutions are to a large extent, based on the substance-field modeling method. Condensed standards incorporate EMS models into the solutions as a substitute for substance field modeling. In addition, several authors have noted the significant degree of repetition amongst the standard solutions, developing their own reduced versions. Soderlin (2002) preferring to use 'rules' as opposed to 'standards', reduced the number of solutions from 76 to 16 rules. Orloff (2003) renames the standard solutions as 'compact standards', and reduces the number to 35. The condensed standards, take into account suggestions put forth by Soderlin (2002), Orloff (2003) and others to generate a set of 27 solutions. Further, the condensed standards, (a) use the language and jargon typical in engineering design, and (b) replace the substance-field models found in the original 76 solutions with the EMS models (Ogot, 2004).

With reference to the first set of condensed standards (Table 4), Condensed Standard 1.3, *placing an additive in the system*, could solve the physical contradiction. More sound from the direct field tends to increase clarity in the system. If microphones are placed on stage in the direct field of each performer, then the clarity should be increased. This may be difficult with movement on stage, so perhaps an additive of a good reproduction of the sound via a better amplification system along with the muddy representation from the center cluster would increase the clarity. Reproducing just the higher frequencies and sending their amplified sound along with the current muddy sound would improve the crispness and therefore the clarity in the system.

3.2.3 DP1 vs. FR3

Angling the speakers to canvas the audience, and not the stage would decrease the occurrences of feedback in the system. Feedback is occurring with the current speakers because the spread is over 180 degrees horizontally; therefore the microphones on the stage can pick up the sound from the speakers. Re-angling the speakers is not possible, so another method of reducing the spread needs to be found. This presents another physical contradiction,

The angle of the speakers needs to change to reduce feedback, but it needs to stay the same due to constraints presented by not being able to move the speakers from current location due to concern for damage to the building.

Using the condensed standard 1.3 again (Table 4), a baffle could be *added* to redirect the sound from penetrating behind the proscenium, the front frame of a stage between the curtain and the audience. This could be attached to the current speaker tree, or added as an architectural element on the wall behind the speakers to reflect the sound that would go behind the proscenium towards the audience. An alternative solution could be to use Condensed Standard 2.6: *Match or mismatch frequencies of elements within the system.* One could add an out of phase signal coming from a speaker near the cluster aimed at the stage area to cancel the signal that produces the feedback (similar to the operation of noise canceling headphones).

Using axiomatic design to establish appropriate contradictions and TRIZ to come up with design solutions to overcome them has resulted in an uncoupled design (*read* good design), where each FR is now independently controlled by a single DP (Table 5).

Table 4. Condensed Standards I (9 solutions): Improving the System with Little or no Change. This class looks at ways to modify a system in order to produce a desired outcome or eliminate an undesired one. An *additive* can be material, energy, voids, systems, sub-systems or super-systems.

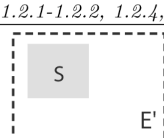
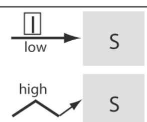
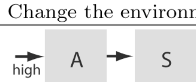
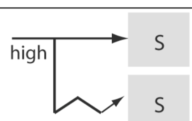
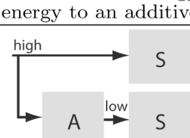
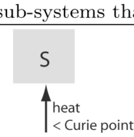
	Problem	Solution
1.1		Without changing the system, add a temporary or permanent, internal or external additive. The additive may or may not be present in the environment *(1.1.2-1.1.4, 1.2.1-1.2.2, 1.2.4, 5.1.1.1-5.1.1.3, 5.1.1.6, 5.1.4, 5.2.2,5.2.3)*
1.2		 Change the environment. *(1.1.5)*
1.3		 If a moderate energy is insufficient, but higher energy is damaging, apply higher energy to an additive that acts on the original system. *(1.1.7)*
1.4		 Both low and high energy levels are required. Use an additive to protect those sub-systems that require low energy. *(1.1.8, 1.2.3)*
1.5		 Heat a material above its Curie point to neutralize harmful magnetic effects. The Curie point is the temperature above which a ferromagnetic material loses its ferromagnetism. *(1.2.5)*
1.6		Use a small amount of a very active additive *(5.1.1.4)*.
1.7		Add additives to a copy or model of the object if it is not possible to add to the original *(5.1.1.7)*.
1.8		Desired additives can be obtained by decomposition of other materials *(5.5.1)*, such as hydrogen from water decomposition.
1.9		Desired additives can be obtained by combining other materials *(5.5.2)*.

Table 5: Uncoupled Axiomatic Design

	DP1	DP2	DP3
FR1			X
FR2		X	
FR3	X		

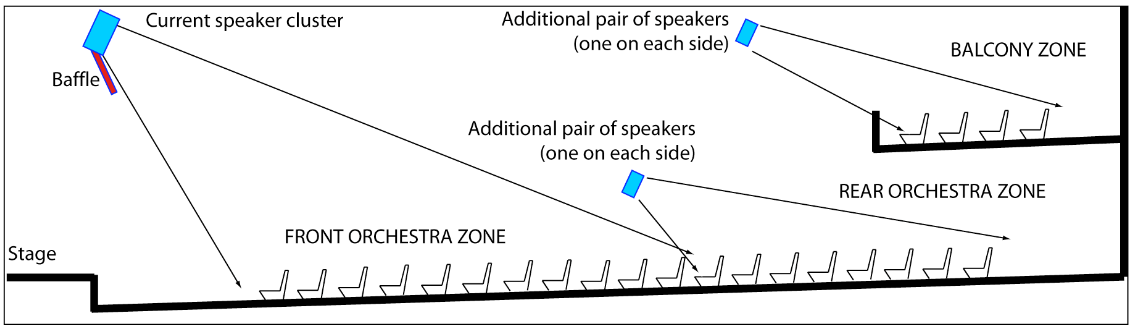


Figure 4 Side view of Schwab Auditorium with suggested improvements

4.0 Final Solution and Concluding Remarks

Employing the TRIZ physical contradiction methodology within an axiomatic design framework has resulted in a solution for the problem with the sound system in Schwab Auditorium (Figure 4), a historic building on the Pennsylvania State University Campus. The final design shown in Figure 4, involves the addition of four side speakers halfway back in the house on the orchestra and balcony levels that would increase the volume for the entire audience more equally than the current system. The addition of baffles, or anti-phase speakers, around the current center cluster will eliminate the problem with feedback on stage, and addition of some high frequency strong speakers near the center cluster should increase the clarity in the house, assuming good clarity can be achieved from the new side speakers. The speakers can be timed to represent the propagation of the actual sound. The entire audience should get better clarity and intensity of the sound without the threat of feedback. Also, except for new side speakers to contend with, these corrections would not destroy the historical appearance of the theater.

References

Savaransky, S., (2000) *Engineering of Creativity: Introduction to TRIZ Methodology of Inventive Problem Solving* Boca Raton: CRC Press.

Ogot M. and Kremer, G. (2004a) *Engineering Design: A Practical Guide* Victoria, BC: Trafford Publishers.

Ogot, M. (2004b), "EMS Models: Adaptation of Engineering Design Black-box Modeling for use in TRIZ", *European TRIZ Association (ETRIA) World Conference, TRIZ Future 2004*, November 3-5, Florence, Italy.

Pahl, G. and Beitz, (1996) *Engineering Design. A Systematic Approach*, 2nd Edition, London, Verlag.

Orloff, M., (2003) *Inventive Thinking through TRIZ: A Practical Guide*, Springer, Berlin.

Soderlin, P., (2002), "TRIZ The simple way", TRIZ Journal, no. 2.

Suh, N.P. (2001), *Axiomatic Design: Advances and Applications* New York: Oxford University Press.

Ahnert, W. and Steffen, F. (1999), *Sound Reinforcement Engineering* London: E & FN Spon.

Georgia State University, HyperPhysics Website, accessed April 11, 2005: http://hyperphysics.phy-astr.gsu.edu/hbase/acoustic/auditcon.html