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# Immaterial Architecture: Composing Space From Sound

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**IMMATERIAL ARCHITECTURE:  
COMPOSING SPACE FROM SOUND**

by

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Bachelor of Architectural Science, Ryerson University, 2009

A design thesis project  
presented to Ryerson University  
in partial fulfillment of the  
requirements for the degree of  
Master of Architecture  
in the Program of  
Architectural Science

Toronto, Ontario, Canada, 2013  
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Yawar Siddiqui

## ABSTRACT

In the post-digital, heterotopic society, human activities have transcended the limiting confines of physical space. The prevailing urban/architectural philosophies that defined programmed spaces by material enclosures and boundaries are less relevant when information, programs and activities transpire independent of such physical fields. Thus, architecture needs to address this emerging paradigm by conceiving new types of traversable spaces. This design thesis develops the use of electroacoustic techniques to generate immaterial sonic enclosures that allow unhindered penetration of light and matter, while blocking out sound within a strepitous environment. Sound is explored as a material for constructing interconnected spaces without physical boundaries. Through the use of the proposed Virtual Sonic Enclosures (VSE), this thesis aims to provide a weak infrastructure rather than an 'object' such as a building to facilitate the seamless networking of spaces and programs to generate new architectural possibilities that reflect contemporary conditions.

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## TABLE OF CONTENTS

<b>Introduction</b> .....	01
<b>Virtual Sonic Enclosure</b> .....	05
<b>The Wall</b> .....	07
<b>Division vs. Diffusion</b> .....	09
<b>Weak Boundaries and Spaces</b> .....	14
<b>Perception of Space</b> .....	22
Auditory Spatial Perception.....	25
Experiment 01 .....	26
Experiment 02 .....	27
<b>Materiality &amp; Immateriality</b> .....	29
<b>Virtual Sonic Enclosure Technical Schematic</b> .....	33
Active Noise Cancellation.....	35
Parametric Array Loudspeakers.....	37
Digital Signal Processing.....	39
<b>Conclusion</b> .....	43
<b>References</b> .....	45
<b>Appendix</b> .....	49

## LIST OF FIGURES

Fig. 01. Internet activity in Egypt during the revolution.

Source: <http://www.opera.com/smw/2011/02/>

Fig. 02. Tweet by Jared Cohen, the founder and Director of Google Ideas,

Source: <http://www.dragonflyeffect.comblogare-you-tweeting-this-revolution>

Fig. 03. Tweets during the Egypt uprising.

Source: <http://www.dragonflyeffect.comblogare-you-tweeting-this-revolution>

Fig. 04. Tahrir Square.

Source: <http://www.businessesgrow.comwp-content/uploads/2011/02/revolution-and-facebook.jpg>

Fig. 05. The Virtual Sonic Enclosure.

Source: Yawar Siddiqui

Fig. 06. The VSE system.

Source: Yawar Siddiqui

Fig. 07. From explicit to implicit space.

Source: Meiss, Pierre von. Elements of architecture, From Form to Place.1990

Fig. 08. Spatial fields defined by vertical elements.

Source: Meiss, Pierre von. Elements of architecture, From Form to Place.1990

Fig. 09. Destruction of the Berlin Wall, 1989.

Source: <http://padresteve.files.wordpress.com/2009/12/berlin-wall-4.jpg>

Fig. 10. Traditional hierarchic industrial society.

Source: Branzi, A. *Weak and diffuse modernity: the world of projects at the beginning of the 21st century.* 2006

Fig. 11. Contemporary network society

Source: Branzi, A. *Weak and diffuse modernity: the world of projects at the beginning of the 21st century.* 2006

Fig. 12. Map of the Internet.

Source: <http://blyon.com/blyon-cdn/opte/maps/static/1069646562.LGL.2D.4096x4096.png>

Fig. 13. Statistics of the increase in mobile devices and wireless services.

Source: ITU Report 2011, Morgan Stanley.

Fig. 14. WiFi Networks throughout the world.

Source: <http://wagle.net/>

Fig. 15. Dense WiFi networks juxtaposed over the built fabric of metropolitan cities such as Chicago (left) and Manhattan (right).

Source: <http://www.tacticalsoundgarden.net/#>

Fig. 16. Sketches by Le Corbusier.

Source: <http://www.vlugt.co.uk/Savoie.html>

Fig. 17. Villa Savoy floor plans.

Source: <http://www.vlugt.co.uk/Savoie.html>

Fig. 18. The Free Plan structure.

Source: <http://www.dieselpunks.org/profiles/blogs/art-history-le-corbusiers>

Fig. 19. Front façade of Sendai Mediatheque.

Source: Toyo Ito Associates. [http://www.toyo-ito.co.jp/WWW/Project\\_List/-2000\\_Project%20List%20photo/2000\\_pl\\_en.html](http://www.toyo-ito.co.jp/WWW/Project_List/-2000_Project%20List%20photo/2000_pl_en.html)

Fig. 20. Sendai Mediatheque. The façade at the ground level.

Source: Toyo Ito Associates. [http://www.toyo-ito.co.jp/WWW/Project\\_List/-2000\\_Project%20List%20photo/2000\\_pl\\_en.html](http://www.toyo-ito.co.jp/WWW/Project_List/-2000_Project%20List%20photo/2000_pl_en.html)

Fig. 21. Sketches by Ito.

Source: Toyo Ito Associates. [http://www.toyo-ito.co.jp/WWW/Project\\_List/-2000\\_Project%20List%20photo/2000\\_pl\\_en.html](http://www.toyo-ito.co.jp/WWW/Project_List/-2000_Project%20List%20photo/2000_pl_en.html)

Fig. 22. Loose partitions and translucent curtains.

Source: Toyo Ito Associates. [http://www.toyo-ito.co.jp/WWW/Project\\_List/-2000\\_Project%20List%20photo/2000\\_pl\\_en.html](http://www.toyo-ito.co.jp/WWW/Project_List/-2000_Project%20List%20photo/2000_pl_en.html)

Fig. 23. Ito. Moveable walls that allow flexible spatial configurations.

Source: Toyo Ito Associates. [http://www.toyo-ito.co.jp/WWW/Project\\_List/-2000\\_Project%20List%20photo/2000\\_pl\\_en.html](http://www.toyo-ito.co.jp/WWW/Project_List/-2000_Project%20List%20photo/2000_pl_en.html)

Fig. 24. Fujimoto, House Na.

Source: <http://www.archdaily.com/tag/sou-fujimoto/>

Fig. 25. Interior view of the living space.

Source: <http://www.archdaily.com/230533/house-na-sou-fujimoto-architects/>

Fig. 26. Fujimoto, House N.

Source: <http://www.archdaily.com/230533/house-na-sou-fujimoto-architects/>

Fig. 27. Fujimoto, House N.

Source: <http://www.archdaily.com/230533/house-na-sou-fujimoto-architects/>

Fig. 28. Fujimoto, House N intersection of juxtaposing programs.

Source: <http://www.archdaily.com/230533/house-na-sou-fujimoto-architects/>

Fig. 29. Tactical Sound Garden.

Source: <http://www.tacticalsoundgarden.net/#>

Fig. 30. integration of wireless infrastructures that actuate physical environments.

Source: <http://www.tacticalsoundgarden.net/#>

Fig. 31. Aerial view of the sound garden.

Source: <http://www.tacticalsoundgarden.net/#>

Fig. 32. Timeline denoting architectural innovations.

Source: Yawar Siddiqui

Fig. 33. Section of St. Mark's, Venice.

Source: Fergusson, James. "Illustrated Handbook of Architecture"

Fig. 34. Melioli visually maps the reverberation and echoes.

Source: Melioli, Matteo. "Inhabiting Soundscape, Architecture of the unseen world"

Fig. 35. Formal expression of the soundscape of the church.

Source: Melioli, Matteo. "Inhabiting Soundscape, Architecture of the unseen world"

Fig. 36. Melioli reveals "ghost spaces".

Source: Melioli, Matteo. "Inhabiting Soundscape, Architecture of the unseen world"

Fig. 37. Auditory spatial perception.

Source: Yawar Siddiqui

Fig. 38. Experiment 01 setup.

Source: Yawar Siddiqui

Fig. 39. Experiment 02 setup.

Source: Yawar Siddiqui

Fig. 40 Graphic simulation showing various sonic environments of varying acoustic intimacy.

Source: Yawar Siddiqui

Fig. 41. Experiments by Kircher exploring echoes.

[http://www.ameet.jp/feature/feature\\_20101021/](http://www.ameet.jp/feature/feature_20101021/)

Fig. 42. Boston Symphony Hall, 1890.

Source: <http://cbsboston.files.wordpress.com/2010/10/bso-twitter.jpg>

Fig. 43. Anechoic Chamber.

Source: <http://acousticenvironments.com/tools-of-the-trade-%E2%80%93-the-anechoic-chamber>

Fig. 44. Resonant Chamber, RVTR, 2011.

Source: RVTR. <http://rvtr.com/research/resonant-chamber/>

Fig. 45. Sonic sculpture by Eusebio Sempere.

Source: <http://nialldebutlear.com/blog/wp-content/uploads/2008/08/sempere20sculpture20web.jpg>

Fig. 46. Sonic metamaterial also known as sonic crystals.

Source: [http://www.science.org.au/nova/newscientist/ns\\_diagrams/072ns\\_004image1.jpg](http://www.science.org.au/nova/newscientist/ns_diagrams/072ns_004image1.jpg)

Fig. 47. Leitner uses the movement of sound to create spaces of sound.

Source: Cantz. "Berhard Leitner Sound:space"

Fig. 48. "Sound Cube", Berhard Leitner.

Source: Cantz. "Berhard Leitner Sound:space"

Fig. 49. "SoundBits" By Robin Minard.

Source: Robin Minard. <http://www.robinminard.com/minard.content.php?id=17&sh=0>

Fig. 50. "SoundBits" Placement of speakers that add to the "spatial timbre"

Source: Robin Minard. <http://www.robinminard.com/minard.content.php?id=17&sh=0>

Fig. 51. Virtual Sonic Enclosure Schematic

Source: Yawar Siddiqui

Fig. 52. The VSE can be expressed into spaces created by sound.

Source: Yawar Siddiqui

Fig. 53. Basic principle of ANC.

Source: Yawar Siddiqui

Fig. 54. Cement plant. Installation of ANC silencer.

Source: R. Ramakrishnan, W. Richardz. "Collaborative Active Noise Control – A case study" Canadian Acoustics 2005.

Fig. 55. Comparison of noise at plant location and receptor location.

Source: R. Ramakrishnan, W. Richardz. "Collaborative Active Noise Control – A case study" Canadian Acoustics 2005.

Fig. 56. ANC setup at the plant.

Source: R. Ramakrishnan, W. Richardz. "Collaborative Active Noise Control – A case study" Canadian Acoustics 2005.

Fig. 57. Performance of the ANC system.

Source: R. Ramakrishnan, W. Richardz. "Collaborative Active Noise Control – A case study" Canadian Acoustics 2005.

Fig. 58 Audio Spotlight AS-16, parametric array loudspeaker.

Source: J. Pompeii. <http://www.holosonics.com/>

Fig. 59. Comparison of sound propagation of a conventional loudspeakers and the PAL.

Source: J. Pompeii. <http://www.holosonics.com/>

Fig. 60. AM demodulation.

Source:<http://www.softwareforeducation.com/wikileki/images/thumb/6/6a/AM-Demodulation.jpg/67px-AM-Demodulation.jpg>

Fig. 61. The simulated results of the cancellation of higher frequencies through the use of PAL.

Source: A. Tan, N. Tanaka. "implementing active noise control using parametric array loudspeaker as system controller" 2006.

Fig. 62. The simulated results of the cancellation of higher frequencies through the use of PAL. Comparison of disturbance and controlled signals.

Source: A. Tan, N. Tanaka. "implementing active noise control using parametric array loudspeaker as system controller" 2006.

Fig. 63. Simple DSP configuration based on FXLMS algorithm for the VSE.

Source: Yawar Siddiqui

Fig. 64. Multi-channel DSP configuration.

Source: Yawar Siddiqui

Fig. 65. This digital control system for feedforward/feedback.

Source: Yawar Siddiqui

Fig. 66. Single channel DSP configuration with FFT integration.

Source: C. Hansen. "Understanding Active Noise Cancellation" 2001.

Fig. 67. VSE Integration in a sonically diverse space.

Source: Yawar Siddiqui

Fig. 68. VSE Studio/Office space.

Source: Yawar Siddiqui

Fig. 69. Sound Map of Office Space.

Source: Yawar Siddiqui

Fig. 70. VSE Spaces.

Source: Yawar Siddiqui

Fig. 71. VSE Experiential Section

Source: Yawar Siddiqui

## LIST OF APPENDICES

### **APPENDIX A**

Active Noise Cancellation Test.....49

### **APPENDIX B**

Active Noise Cancellation Test with PAL.....50

AudiospotlightAS-16Specifications.....51

MatLab FXLMS Algorithm.....53

### **APPENDIX C**

Varying Frequencies.....56

## INTRODUCTION

“We put thirty spokes together and call it a wheel;  
But it is on the space where there is nothing  
that the utility of the wheel depends.  
We turn clay to make a vessel;  
But it is on the space where there is nothing  
that the utility of the vessel depends.  
We pierce doors and windows to make a house;  
and it is in these spaces where there is nothing  
that the utility of the house depends.  
Therefore, just as we take advantage of what is,  
We should recognize the utility of what is not.”

-Lao-tzu. Tao Te Ching. 6th century BC.

Space is a paradoxical concept. An abstract notion describing what we humans consider to be the ever-present ‘empty’ medium through which we define the existence of not just ourselves, but also of the place in which we exist. From interstellar to personal, space is connected to the very impulse of our being. As Lao-tzu understands, it is in the emptiness in which the understanding of space lies, yet it is never truly empty. As perceptive beings, we exist in the space of sound, as “no sound exists outside of space, and no space is ever truly silent” (Ripley, 2007). The ubiquity of sound in space defines the nature of the environment in which we live and function as a species. The manner in which a space sounds reveals a mental image as we decipher data such as volume, materiality, program, location and the character of a space. Sonically, spaces exist beyond their visual and geometrical understanding through the use of echoes and reverberations. Sound presents the possibility of an architecture that can generate and excel interactions and activities in the contemporary urban condition.

Sound informs us of our condition in history (Attali, 1985). In the Islamic culture, the sound of the *adhaan* (the call to prayer) would communicate the temporary suspension of all activities and would signal the community to join together in prayer. Similarly, in medieval France, the ability to hear the sound of the town bell determined whether someone was considered a citizen of that town (Blessner and Salter, 2007). Anyone living outside the audible range of the bell was considered a foreigner. In the iPhone generation where activities and spaces overlap irrespective of intimacy or personal space, we see that in increasingly noise saturated environments individuals escape physical reality with the aid of sound by putting on headphones and creating a personal zone of desired space. From the iPhone to the call to prayer, sound is the earliest form of communication that defines cultures and spatial associations. Sound has increasingly become the definer of space, as sound not only reveals the character of a space but also communicates sociocultural conventions.

Architecture has always been an agent of socioeconomic and cultural paradigms that have transpired throughout human history as it represents, and conveys the societal predilection of cultural archetypes. By

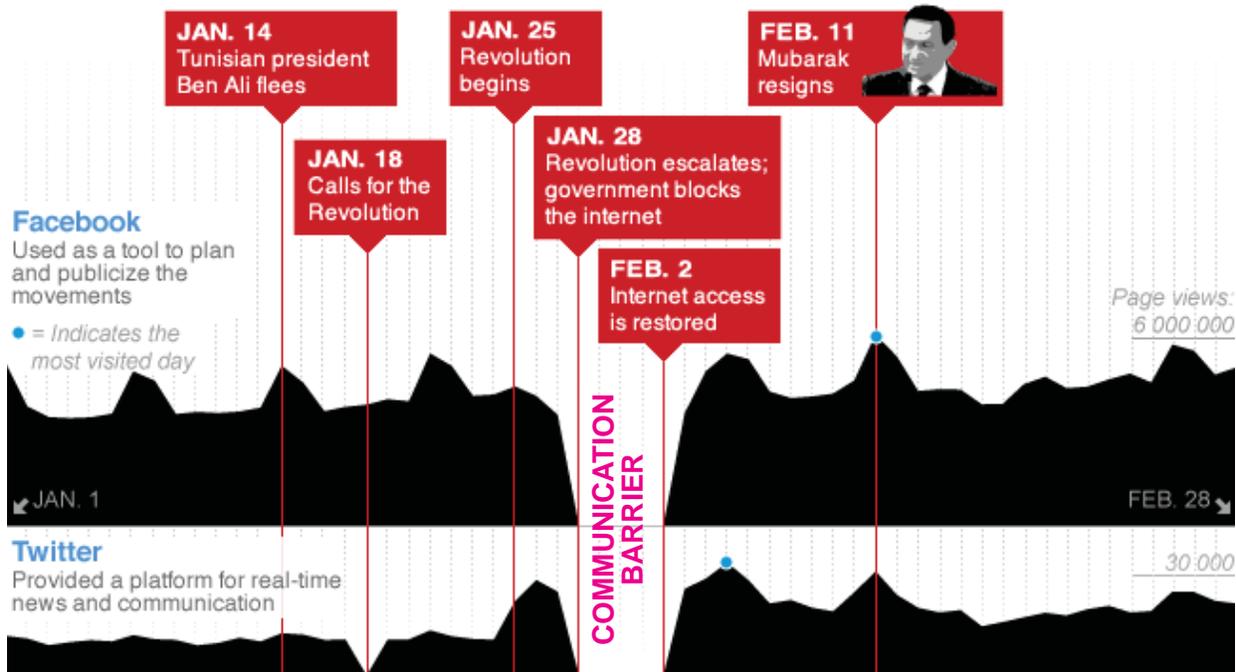


Fig. 01. Internet activity in Egypt during the revolution

One Egyptian says, "facebook used to set the date, twitter used to share logistics, youtube to show the world, all to connect people" #jan25

8:36 AM Jan 27th via Twitter for BlackBerry®  
Retweeted by 100+ people

Reply Retweet

**JaredCohen**  
Jared Cohen

Fig. 02. Tweet by Jared Cohen, the founder and Director of Google Ideas,

**@Ghonim**  
Wael Ghonim

Everyone come to Tahrir now we need you we are no less than 10,000 and no more police #JAN25

25 Jan via Twitter for BlackBerry® ☆ Favorite Retweet Reply

Fig. 03. Tweets. made possible for the people of Egypt to openly communicate and later congressional communication for the uprising denouncing President Mubarak. This particular tweet was sent via Blackberry.

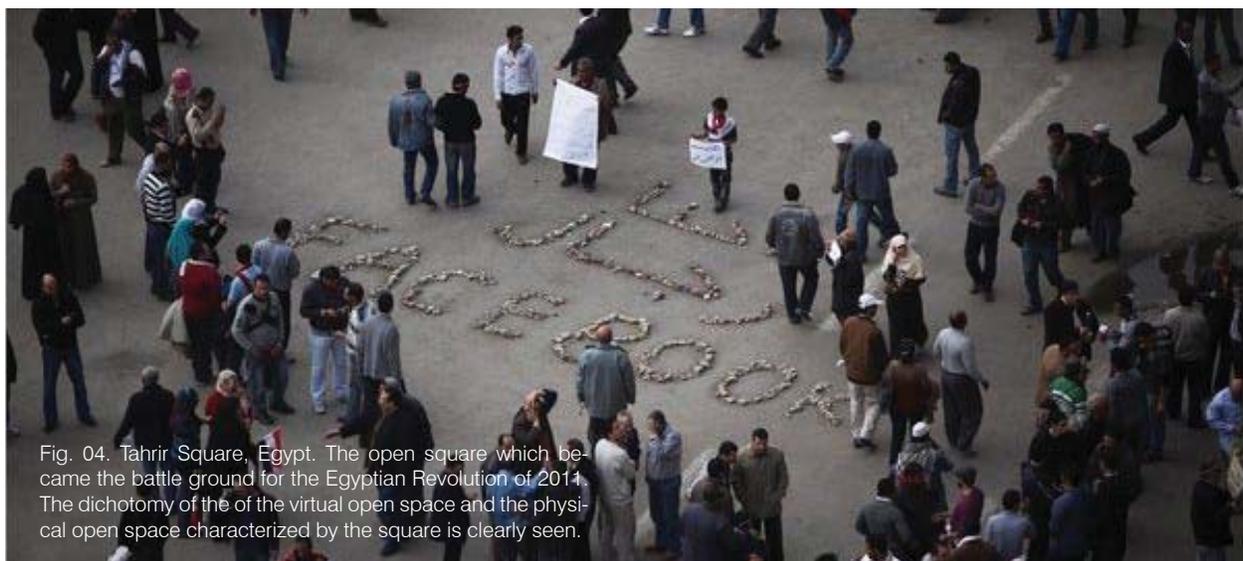


Fig. 04. Tahrir Square, Egypt. The open square which became the battle ground for the Egyptian Revolution of 2011. The dichotomy of the of the virtual open space and the physical open space characterized by the square is clearly seen.

formulating spaces influenced by its sociocultural precedents and other environmental factors, architecture describes the circumstances and the nature of how we live and function as a society. “The societal function of architecture is the innovative ordering and framing of communicative interactions” (Schumacher, 2011). In the post-digital, heterotopic society, ubiquitous wireless networks of information have transcended human interrelations and activities beyond the limiting confines of physical space. The prevailing urban/architectural models that determined spatial composition by means of material enclosures and boundaries such as walls are less relevant when information, programs and activities transpire independent of such physical elements. Architecture’s task now is the organization of and articulation of societal complexities of the post-fordist network society (Schumacher, 2011).

Contemporary cultural mechanics have started to exploit the dichotomy of the virtual and physical space as it is clearly evident from the increased use of wireless devices such as smartphones and tablets. These devices virtually connect the whole world despite the physical limitations of space and time, hence, bringing upon a revolutionary change in personal and global affairs. This is acutely illustrated through the 2011 Arab Spring uprising supported by the immaterial wireless networks which helped topple a 30 year dictatorship that was initiated and conducted through the exploitation of Facebook and other social media peripherals including YouTube and Twitter. We are no longer bound by physicality when the emerging virtual realm creates a space that enables peoples to communicate and share ideas free of any spatial, social, and cultural limitations. Limitations which would otherwise be imposed by sanctions, borders, barriers, and walls, are dematerializing as immaterial networks connect most of the world. With the decentralization of ideas and information free of any barriers and constraints, a new social standard towards transparent and seamless interaction of ideas and activities needs to be addressed architecturally. The architectural philosophies inherited from the models of the twentieth century are irresponsive to the contemporary network society; hence, this thesis explores the opportunity of a “traversable architecture that guarantees the penetration of territory and space, no longer marked by closed confines, but by open filters” (Branzi, 2006) The suggested open filters assert the construction of spaces are no longer bound by borders and barriers but by open flows of information, ideas and cultures. Architecture and therefore, cities must generate, reflect and activate life, while organizing their structure to precipitate life and movement (Castell, 2007).

Given the contemporary urban condition, this design thesis argues to identify and define sound as a material through which a new type of traversable architecture can emerge. The aim of this thesis is to develop the use of electroacoustic techniques, through the incorporation of physical and phenomenological applications of sound to compose interconnected spaces purely out of sound and/or the lack thereof. Consequently, this may reveal architectures existing beyond the boundaries of physicality – an immaterial architecture. As it is explored, sound holds the potential to create permeable enclosures that allow people to freely move, and see through, while creating an invisible sonic barrier – the Virtual Sonic Enclosure.

**“A traversable architecture that guarantees the penetration of territory and space, no longer marked by closed confines, but by open filters.” (Branzi, 2006)**



Fig. 05. The Virtual Sonic Enclosure. Dematerialized boundaries allow the penetration of not only spaces but also culture.

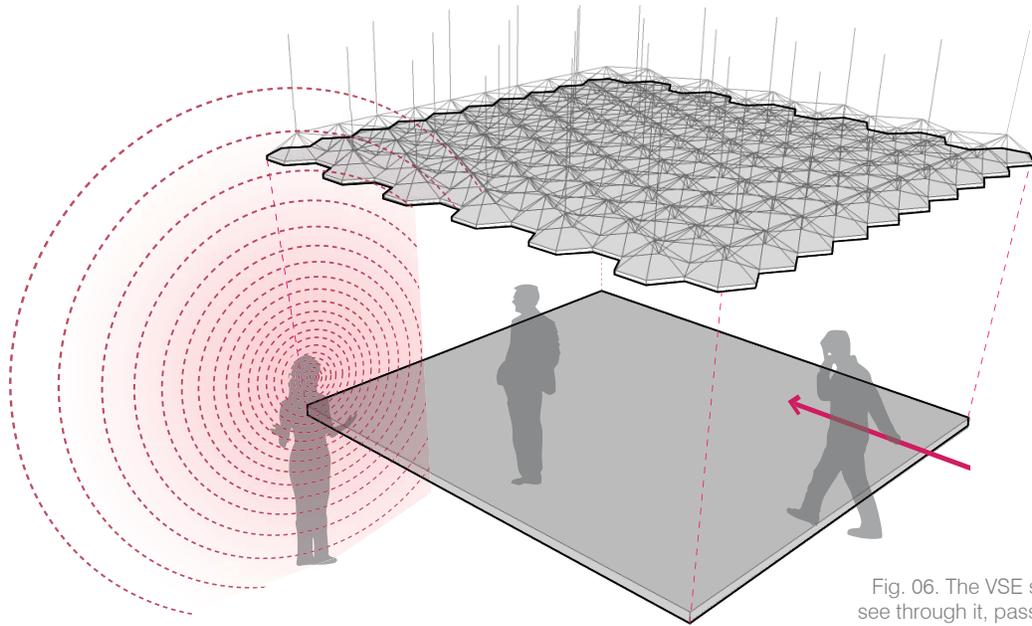


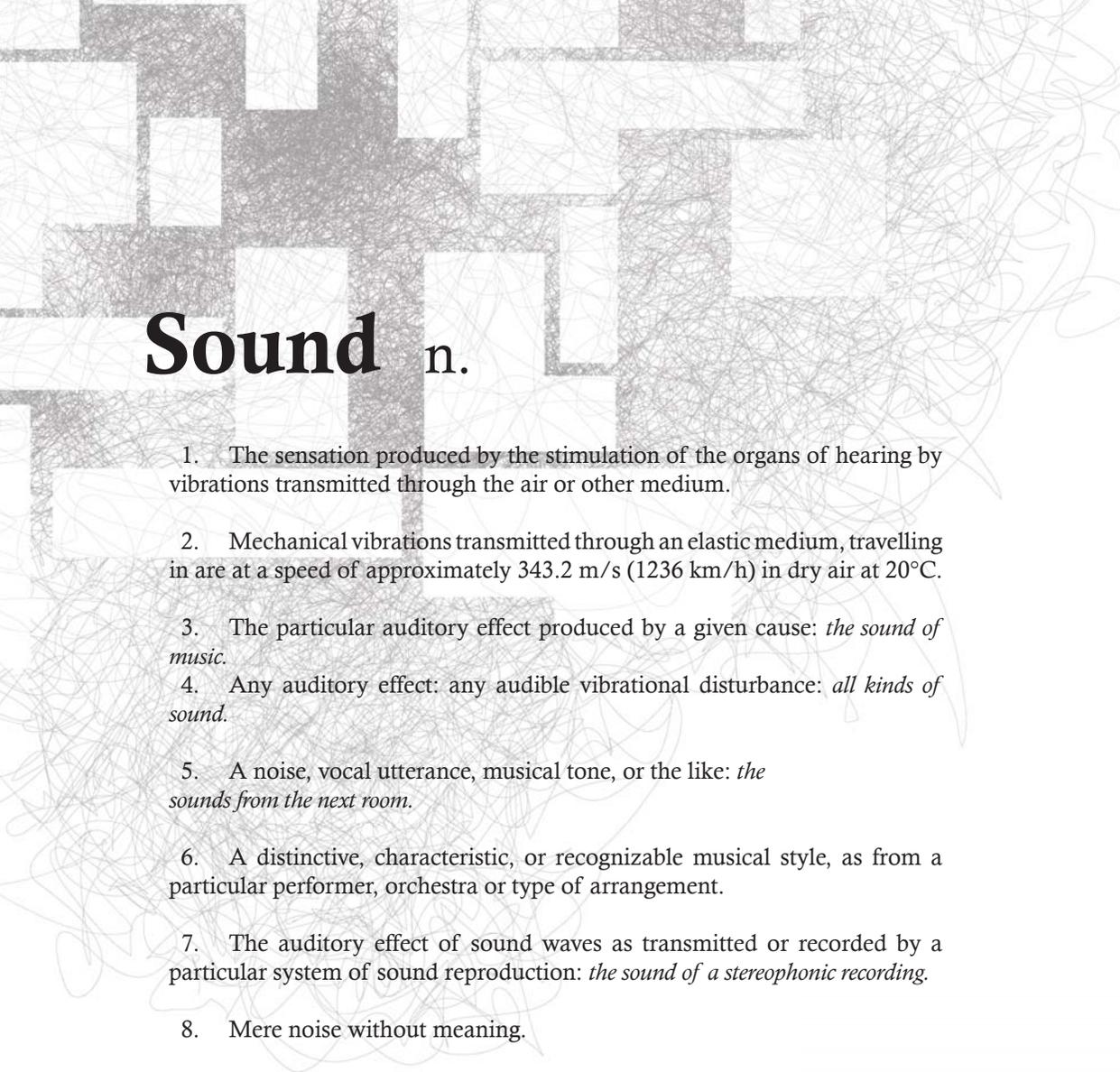
Fig. 06. The VSE system, allows people to see through it, pass through it but filters out sound.

## THE VIRTUAL SONIC ENCLOSURE

The Virtual Sonic Enclosure (VSE) is an immaterial enclosure constructed purely out of sound. It is an envelope that allows the unobstructed penetration of sight and physical movement while filtering out sound. The VSE technology is based on principles of active noise cancellation to generate invisible zone(s) of silence around the user. This is an attempt to conceive architecture that is designed and built by sound and/or the lack thereof, thus, generating spaces without the employment of physical materiality. As a result, this eludes at the possibility of creating new traversable interconnected spaces defined by sound.

The project explores the interactions between the technical understandings of the manipulation of sound as a material to instigate new meaning that lies within the shaping of the physical world which could inform the idea of immaterial architecture. The understanding of the correlation of sound and space has two facets that will be discussed in this thesis. While phenomenology gives us the understanding of the experience of the space, the physical understanding of the phenomenon of sound provides scientific insight into the physical execution of the experience in that space. This thesis discusses the phenomenological understanding of sound and how such an understanding can communicate architectural space beyond physical representation. To do this, the execution of the VSE system takes into account the perceptive power of the mind to create illusory spaces expressed through electroacoustic means.

The thesis explores the VSE as an interface that communicates the contemporary urban conditions. Through the use of the proposed VSE, this thesis aims to provide a weak infrastructure rather than an 'object' such as a building to facilitate the seamless networking of spaces and programs to generate new architectural possibilities. The VSE explores the need for spaces that encourage transparency in society and culture. Architecture, thus, has the potential to dematerialize to the point that it is completely invisible. - an immaterial architecture.



# Sound n.

1. The sensation produced by the stimulation of the organs of hearing by vibrations transmitted through the air or other medium.
2. Mechanical vibrations transmitted through an elastic medium, travelling in are at a speed of approximately 343.2 m/s (1236 km/h) in dry air at 20°C.
3. The particular auditory effect produced by a given cause: *the sound of music.*
4. Any auditory effect: any audible vibrational disturbance: *all kinds of sound.*
5. A noise, vocal utterance, musical tone, or the like: *the sounds from the next room.*
6. A distinctive, characteristic, or recognizable musical style, as from a particular performer, orchestra or type of arrangement.
7. The auditory effect of sound waves as transmitted or recorded by a particular system of sound reproduction: *the sound of a stereophonic recording.*
8. Mere noise without meaning.

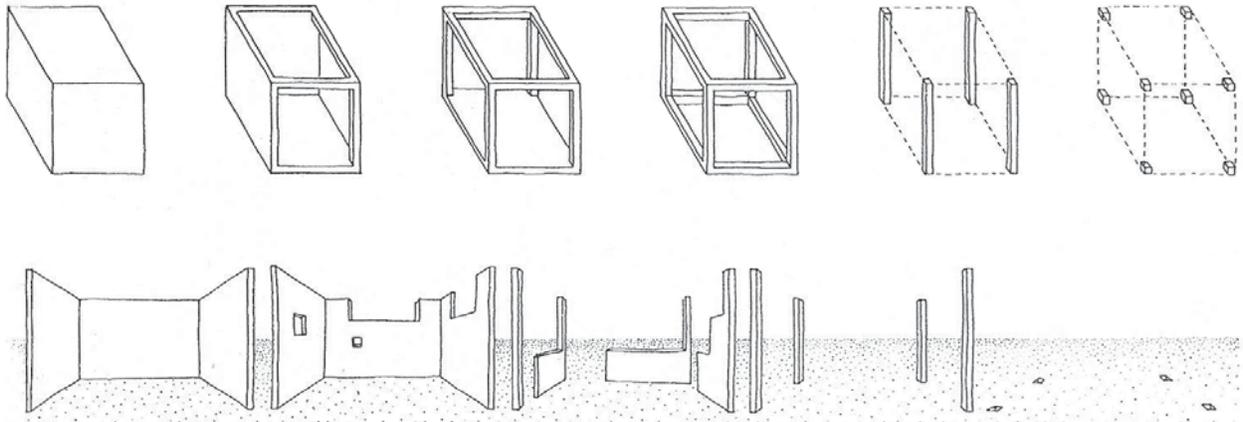


Fig. 07. From explicit to implicit space defined by various spatial cues.

## THE WALL

“The existence of place is held to be obvious from the fact of mutual replacement. Where water now is, there in turn, when the water has gone out as from a vessel, air is present; and at another time another body occupies this same place.” (Aristotle, Physics, IV, 1)

Aristotle defines space as a hollow container (Meiss, 1990). Architectural expression is based on the premise of designing this hollow container - space. The utility of architecture depends on the creation of space defined by such elements (not limited to) as walls and partitions. Architectural space is conceived from the correlation between objects, boundaries and planes, which define its spatial limits. Depending on the architectural expression of these limits may be more or less explicit, which can constitute continuous surfaces forming an uninterrupted boundary or may comprise of just a few cues such as expressed by four columns, colour, light or even sound (Meiss, 1990). For instance, the space inside a cube is constructed by six planes that define its spatial limits. However, if these planes were to dematerialize and simply be ‘implied’ by defining only the corners of the cube, the observers of the space would actively recognize the space to be a cube space. Figure 07 illustrates the dematerialization of the cube while still communicating a cube space by strategically maintaining defining cues. As perceptive beings we consciously or unconsciously register these cues based on sensory stimulation of sight, touch and sound. This allows the communication of space through implicit or explicit means. “The user establishes relationships, enabling the interpretation of an implicit limit” (Meiss, 1990). This simulates the genesis of a space

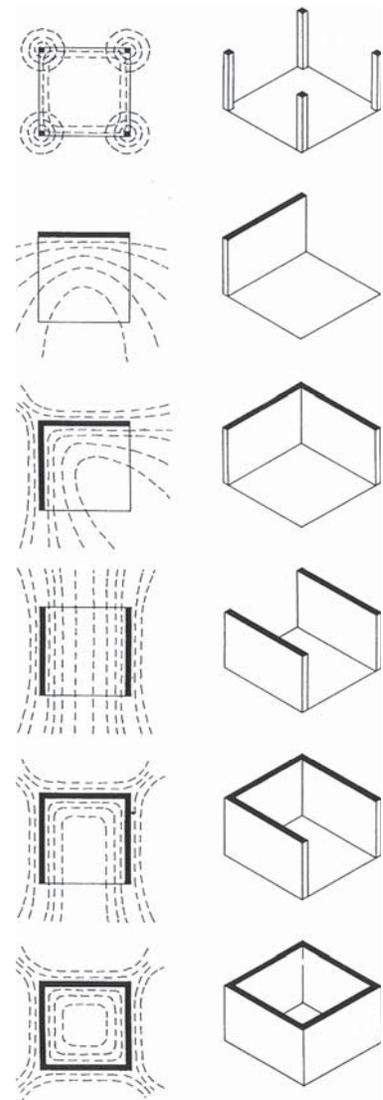


Fig. 08. Different spatial fields on the same square plan by means of varying vertical elements.

defined by minimal cues. The resulting 'image' of the space is defined by such limits is not the objective fact of space as it is, but the experience of space that passes through subjective filter of perception conditioned by our past experiences, and cultural dispositions (Meiss, 1990). Limits can also be defined by sound as it will be discussed through auditory spatial perception. Consequently, the thesis explores the use of sound to generate such type of explicit and implicit limits. The Virtual Sound Enclosure creates a novel spatial situation where it is visually and physically implicit yet very explicit sonically. Does this technique of sonic definition constitute spatial limits and boundaries? Through the phenomenological understand of space, sonic 'walls' can be erected that explicitly define a space.

Spaces have a fundamental prerequisite of providing various degrees of intimacy based on the function of the space. This intimacy can be achieved through blocking various stimuli that are used to perceive space such as a wall. The wall is a transitional threshold that divides juxtaposing spaces in architecture. Michael Graves addresses the wall as the mediator between the sacred interior and the profane exterior. An opaque wall, creates spatial boundaries, similarly, the dematerialization of walls into permeable thresholds (sonic walls), spaces can achieve a state of liminality through which different characteristics and expression of space can emerge. Walls can define spatial characteristics of layering, dissolution, blurring and ambiguity that transform the user experience as they move through it. Such spaces can lead the user to question their surroundings and stimulate a heightened awareness of the space. How this threshold is conceived is what defines the space. In history, the erection and dissolution of walls have brought great transformations in social conditions. The dissolution of the Berlin Wall triggered by the need for a transparent and democratic society transformed the socio-political landscape of Europe that is defined by such transformative thresholds. The opposite could be said about the adamant erection of the Wall dividing Israel and Palestine. The proposed sonic enclosure provides the possibility of just such thresholds between distinct spaces that generate transformative spaces.

Fig. 09. (below) Destruction of the Berlin Wall, 1989.



## DIVISION vs DIFFUSION

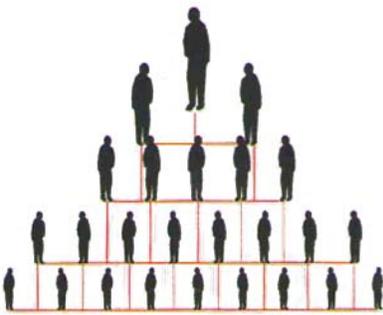


Fig. 10. Traditional hierarchic industrial society

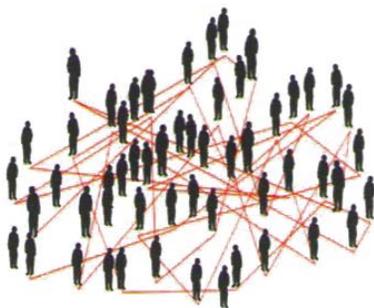


Fig. 11. Contemporary network society

The centralized, linear flow of information and activities driven by the industrial process of standardization and mass production, established the emergence of the modern corporation in the 19th and 20th century (Stalder, 2001). The modern system instituted a rigid hierarchical organization of information and orders flowing top to bottom similar to the sequential flow of a factory assembly line. Architecturally, this linear flow of information and materials transpired into the centralized systems of spatial organization exemplified by strict boundaries defined by fixed functionalities. Deriving from this philosophy emerged a Taylorist organization of spaces designed to increase bureaucratic efficiency. “Centralization meant that even as the scale kept on increasing, things that logically belonged together in the sense that they constituted a single process were also geographically located together”. After the Second World War, the global scenario began to shift from the centralized form of information processing and communication to a decentralized global network.

Advances in telecommunication technologies, such as the radio and the introduction of the first transatlantic telephone line in the 1950’s, marked the first step towards networking people and spaces throughout the world (Stalder, 2001). The social and economic processes of sharing information and ideas began to experience a time-space compression, where information was relayed instantaneously and free of any spatial limitations (Harvey, 1990). As a result, spaces and locales “saw a significant acceleration in the pace of life concomitant with a dissolution or collapse of traditional spatial co-ordinates”, (Jon and Thrift, 2001). As modes of communication increased in scope of processing and bandwidth capacity in the 21st century, more complex information could be communicated

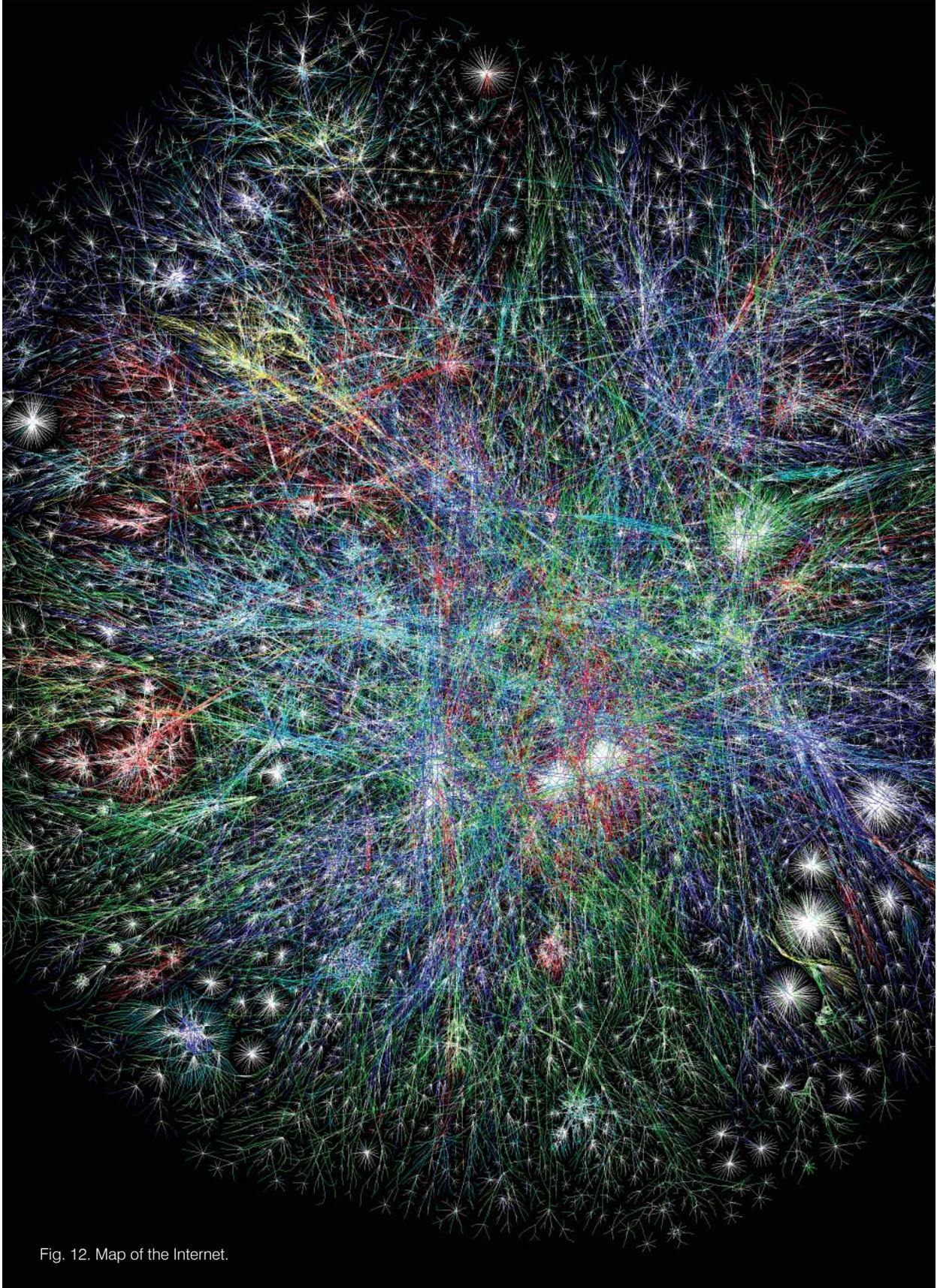


Fig. 12. Map of the Internet.

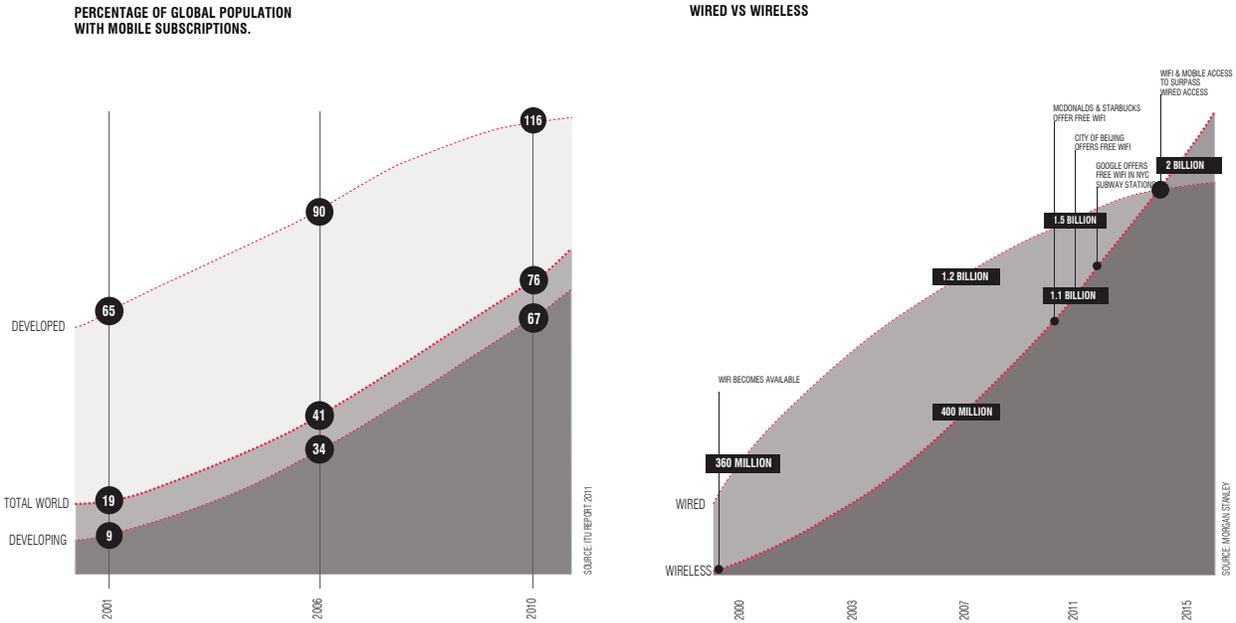


Fig. 13. Statistics of the increase in mobile devices and wireless services.

wirelessly, known as WiFi. With the interconnected flows of capital, information, technology, organizational interactions, images, sounds and symbols, this new space of flows became an expression of the changing contemporary spatial organization (Castells, 1996).

“The emergence of the network enterprise as a new form of economic activity, with its highly decentralized form of work and management, tends to blur the functional distinction between spaces of work and space of residence” (Castells, 1996, pp85)

Until recently, modern architecture responded to linear strategies by designing spaces corresponding to fixed functionalities and programs defined by rigid boundaries such as walls and partitions. With the integration of wireless information networks within a physical urban fabric, the long held rigid boundaries of the modernist urban and architectural landscapes have begun to dematerialize from the fixed division of program and space to allow autonomous diffusion of heterotopic fields. As the Web 2.0 (WiFi) progressively connects the world, independent of any border or barrier, programs and spaces are becoming increasingly ephemeral. The built fabric needs to “reconceptualise new forms of spatial arrangements under the new technological paradigm” (Castells. 1996, pp. 146). This form of ubiquitous networks and computing prompts a new type of ubiquitous architecture.

In just a few years, technological advances in computers and hand-held devices have dissolved the relationship of boundaries and fixed space. For instance, a smartphone simultaneously connects distant global locations where one can wirelessly attend an international conference in Tokyo, download the latest hit song from Korea, set up a dinner date and catch up on the daily news, all while drinking an Indian chai at a French café in

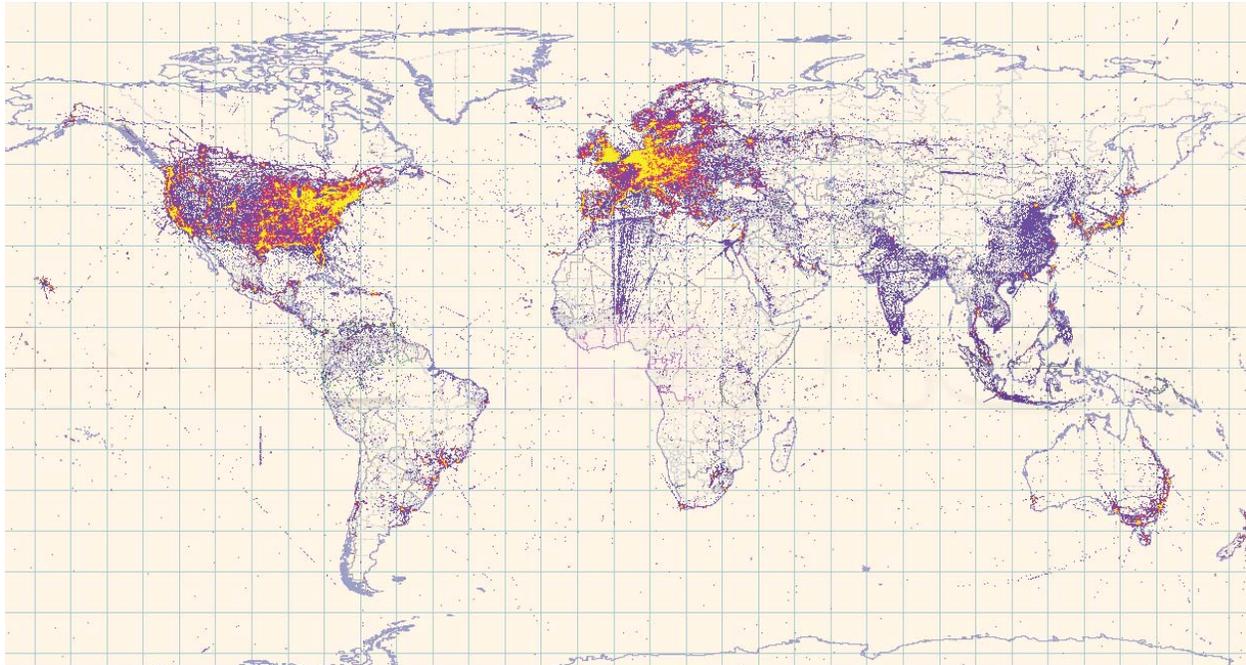


Fig. 14. WiFi Networks throughout the world

downtown Toronto. As elicited by the wireless era,

“...our buildings and urban environments need fewer specialized spaces built around sites of accumulation and resource availability and more versatile, hospitable, accommodating space that simply attract occupation and can serve diverse purposes as required.” (Mitchell, 2004)

Though the development of immaterial networks of communications is relatively new with retrospect to modern architectural history, the concept of autonomous spatial and programmatic diffusion has been the topic of discussion by architectural theorists such as Archigram and Archizoom since the 1960's. Andrea Branzi, an associate of the Archizoom group, often evaluated the attitude of modern architecture and urbanism as a static rigid ideology that did not recognize the contemporary weak urban scenario.

“Contemporary architecture still attributes its own foundation to the acts of building, constructing visible space; metaphors limited to a single building and single typologies, and do not take the opportunity to represent a dispersed, inverted and immaterial urban condition.” (Branzi, 2006)

Branzi's disposition towards contemporary architecture advances the idea of what he calls “weak spaces”. Derived from Gianni Vattimo's hermeneutic philosophies of “weak thought”, the term weak does not refer to frailty or infirmity; rather it is a concept epitomizing loose and flexible relationships between space, program and user. As it is evident in the current ephemeral urban condition, the application of weak spaces encourages the development of transient autonomous programmatic systems. An early example of a weak system may have been described in Yona Friedman's work on the *Spatial City* during the modern period. His work was directed towards finding a mode for architecture to be free and loose. Friedman suggested mobile architecture

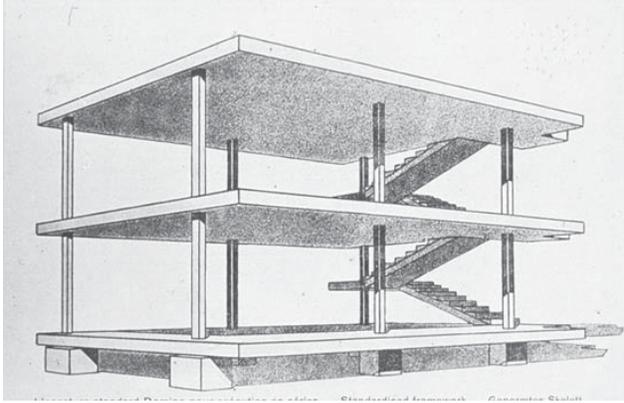


Fig. 15. Dense WiFi networks juxtaposed over the built fabric of metropolitan cities such as Chicago (left) and Manhattan (right).

that would not be subjected to a permanent context, rather, it would, as Branzi states; “invoke the melding of places based on autonomous programmatic relationships – a “genetic metropolis”.

“We can imagine in Imperial Rome, in current day Mumbai, or in the great African capitals like Lagos: an urban reality where architecture is of human presences, relation, intersects and exchanges that completely fill the space. Architecture no longer defines a permanent segmentation of space, but becomes the theater of a vast elastic (in other words reversible) modification of infrastructures, services and metropolitan underpinnings from the bottom up.” (Branzi, 2006)

With the superimposed structures of virtual networks over the built environment, the metropolitan fabric has been “transformed by the interface between electronic communication and physical interaction by the combination of networks and places” (Castells, 1989). This global reality is compelling urban and architectural design to acknowledge the demand for traversable spaces that allow the diffusion of spaces, programs, and functions to engender a rich cultural and spatial osmosis. Thus, architecture can “accelerate society’s transformation through a careful agencing of spaces and events.” (Tschumi, 2004). By dematerializing barriers and forming weak boundaries that act as open filters, architecture can reveal the potential to diffuse numerous programs and spaces to explore novel architectural solutions.



## WEAK BOUNDARIES AND SPACES

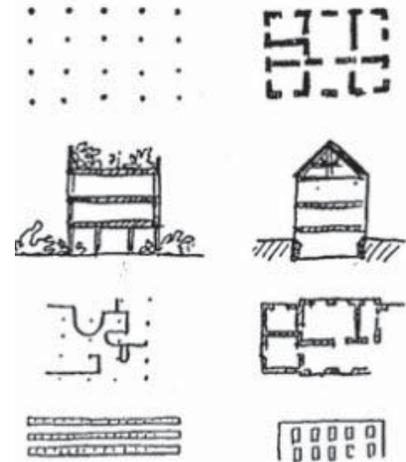


Fig. 16. Sketches by Le Corbusier illustrating the freedom of spatial expression

Historically, architectural and spatial innovation engages with the idea of defining and designing spaces that allow for new possibilities of program, function and experience. One such innovation in the modern period was the Free Plan by Le Corbusier. Traditionally, spatial organization used to be the derivative of limiting factors, such as structural walls. Other than conceiving a cost effective and easy to construct system, Le Corbusier pioneered the Free Plan to liberate fixed space from the confines of structural load-bearing walls by employing columns to support the load of the building. Spaces were no longer limited by the calculated placement of structural walls as the columns freed the interior space to discover new possibilities of spatial and programmatic organization. Spaces and programs were now able to interact and, if intended, intersect as the new architecture started to explore innovative forms and expressions of space. In contemporary architecture several design studios have started to explore spatial strategies that exemplify weak boundaries and spaces.

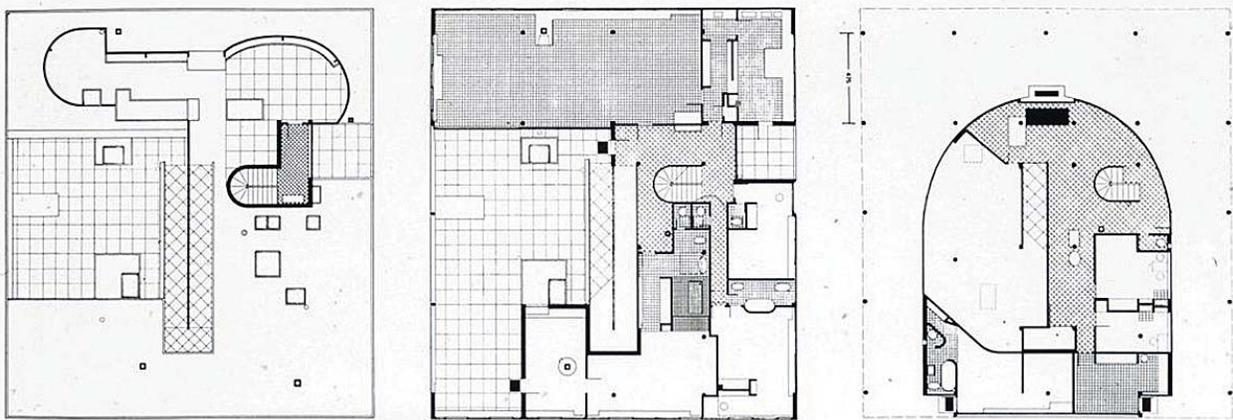


Fig. 17. Villa Savoy floor plans illustrates in practicality the Free Plan and formulation of new types of spatial and programmatic expression

Fig. 18. (Top) The Free Plan structure.



Fig. 19. Front façade of Sendai Mediatheque.



Fig. 20. The façade at the ground level retreats as fields of the outdoor space of the city melds with the interior space. This illustrates the ubiquitous plane of activity that activates unhindered flow of activities.

## Toyo Ito, Sendai Mediatheque, 2001.

One of the most prominent contemporary examples of spatial and programmatic diffusion through the dematerialization of rigid boundaries is the Sendai Mediatheque by Toyo Ito, 1997-2001. This project recognizes the emergence of the internet/media age foreshadowing new types of architectural typologies, and houses a state-of-the-art media “zone”, rather than the assumed media “library”. From the very genesis of conception, Ito realized the ephemeral fabric of contemporary media space, and hence, expanded the concept of ‘fluid’ and ‘barriers free’ space into a vast expanse of open fields. Initially intended to be barrier free in terms of accessibility, Ito advanced this idea while recognizing the loose and weak fabric of digital information and media to create spaces free of fixed barriers and boundaries to mutually influence autonomous diffusion of programs and spaces. Instead of erecting solid rectilinear walls for defining programs, Ito designed semi-permeable, translucent membranes – a curtain (Figure. 22,23). This design strategy fosters the concept of free and open movement as the user is at liberty to choose between various possibilities – “they make their own path” (Ito, 2007). Even as one enters the building, the façade which distinguishes the boundaries of indoor space and outdoor space are blurred as the whole façade opens up and invites the outside in and the inside out. Architecture becomes immaterial as the juxtaposed programs meld together and there is a realization of intersecting spaces that release architecture from

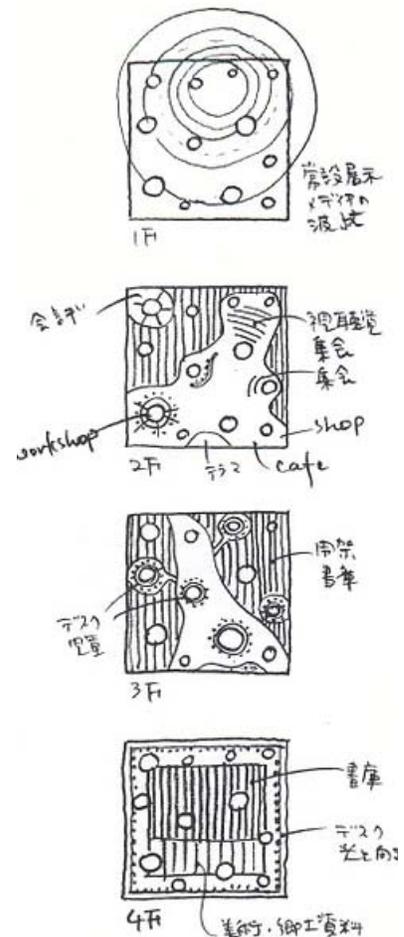


Fig. 21. Sketches by Ito illustrating unhindered open space activated by ubiquitous planes.



Fig. 22. Ito employs loose partitions such as a translucent curtain to distinguish private administrative spaces rather than a solid wall. This demonstrates weak boundaries that allow spatial cohesion and transferability.



Fig. 23. Drawing on the idea of ephemerality, Ito designs moveable walls that allow flexible spatial configurations.

the rigid limits of physical partitions, and engender new spatial and social interactions.

“I took ‘barrier free’ to mean also freedom from administrative constraints. It is precisely because I wanted to restore vitality and joy to the spaces of public facilities that the tubes, which caused many people so much trouble to erect, came to exist.” (Ito, 2004)

The spatial organization in Sendai Mediatheque is meant to be reflective of the immaterial, ephemeral information space. By loosely defining programs and space through the use of weak and transparent partitions, the space connects the immaterial information space with the physical space. The concept of ephemerality of partitions and walls, borrowed from precedents such as the Pompidou Center, the Mediatheque was coupled with Ito’s conception of free program and free space. The Sendai Mediatheque illustrates architecture exploring the limits and application of weak boundaries to initiate and allow brand new spatial and programmatic opportunities.

## Sou Fujimoto, House NA, 2010, and House N, 2008.

Heavily inspired by Sendai Mediatheque, the term ‘Primitive Future’ coined by Japanese architect Sou Fujimoto describes the spatial and programmatic conditions in primitive interpretations of space – such as the cave (Fujimoto, 2010). Fujimoto’s design exploration begins by, “going back to the beginning of architecture”. Similar to the cave, the user defines the space as the architecture only provides the infrastructure. Fujimoto’s House Na (2010) takes radical steps towards redefining architecture to realize the relationship of the human and the space. “I don’t want to just create a crazy house, I like to find the most fundamental, and unexpected aspects of human life” (Fujimoto, 2011). By organizing space absent of barriers and boundaries, House Na explores the potential of programs that converge at different points of the house creating interesting and novel spatial conditions. Instead of using walls to create weak boundaries between programs and spaces, Fujimoto uses the undulation of numerous platforms denoting free program. This architecture describes “nomadic” conditions (Fujimoto, 2011), similar to the contemporary nomadic urban condition (Mitchell, 2004).



Fig. 24. House Na. Fujimoto forms transparent spaces that are not defined by partitions but by undulating platforms.



Fig. 25. Interior view of the living space. This illustrates a rich diffusion of activities and spaces that allow free movement of users and programs.

“The relationship of mobile bodies to sedentary structures have loosened and destabilized: inhabitation is less about doing what some designer or manager explicitly intended in a space, and more about imaginative, ad hoc appropriation for unanticipated purposes” (Mitchell, 2004)



Fig. 26. House N. The large openings act as open filters diffusing spaces and programs.

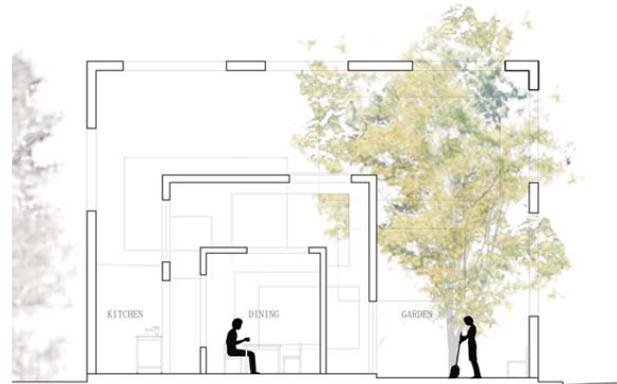


Fig. 27. House N. This illustrates the layering of spaces that introduce intersecting liminal spaces that actuate novel spatial relationships with the user.

Another such project by Fujimoto that explores novel spatial interactions is the House N. Similar to House Na, this design explores possibilities of situating juxtaposed programs and spaces separated not by solid walls but by semi-permeable filters created by large openings that allow the interaction between the inside and outside. The design of the house is a simple layering of boxes that impose interesting liminal spaces within each other. The outer box covers the whole site, with smaller boxes allocating the living space. The interior boxes which house the living space also provide a similar function where the large openings create in-between spaces of interaction within the dwelling. This system of semi-permeable spaces within each other creates a “positively confusing situation of inside and outside” (Fujimoto, 2011). This ‘positive confusion’ enforces the idea and process of spatial and programmatic osmosis.



Fig. 28. In the House N Fujimoto describes the intersection of two juxtaposing programs. This induces 'positive confusion', enforcing the idea of spatial and programmatic osmosis

The Free plan liberated architecture from deterministic structures, while the Sendai Mediatheque liberates architecture from the confines of barriers and boundaries to influence free space and free program. Houses Na and N explore different strategies to liberate the user to explore novel spatial conditions. Ultimately, these innovations were driven by the perpetual need to liberate architecture from the rigid, traditional limitations, and accommodate the organization of space that actuates not only the free flow of information but also of space, program and social interactions.

"By flows I understand purposeful, repetitive, programmable sequences of exchange and interaction between physically disjointed positions held by social actors" (Castells. 1996).



Fig. 29. Tactical Sound Garden. Sonic spaces activated by the use of smartphones.

## Mark Shepard, Tactical Sound Garden, 2007

With the overlaying of dense networks of information over the built fabric of cities, there are a few projects that have begun to explore the implications and applications of merging physical space with virtual networks. As wireless devices such as smartphones and tablets continue to dominate human lives, architecture needs to start exploring ways of integrating ubiquitous wireless networks with physical space. Once such project that explores this association is the Tactical Sound Garden (TSG) project initiated by architect Mark Shepard.

“Given the ubiquity of mobile devices and wireless networks, and their proliferation throughout increasingly diverse and sometimes unexpected urban sites, what opportunities- and dilemmas- emerge for the design of public space in contemporary cities?” (Shepard, 2007)

The TSG is an attempt to articulate physical public space actuated by the interaction of the wireless infrastructure of communication to redefine, in contemporary terms, the use of public space via wireless devices such as smartphones. This project draws from the emerging virtual communities of the web and translates it to the physical world based around the concept of cultivating public “sound gardens”. Through the use of smartphones the TSG provides an open source software platform that enables anyone within a Wi-Fi zone to digitally “plant” sounds at specific locations throughout the city. The user actively participates in the creation of sonic environments where other users can interact and participate in observing sounds planted by previous users of the space. The TSG enables the establishment of shared social spaces within which people collaborate on the cultivation of sonic environments. Shepard extends the practice of ‘playlist sharing’

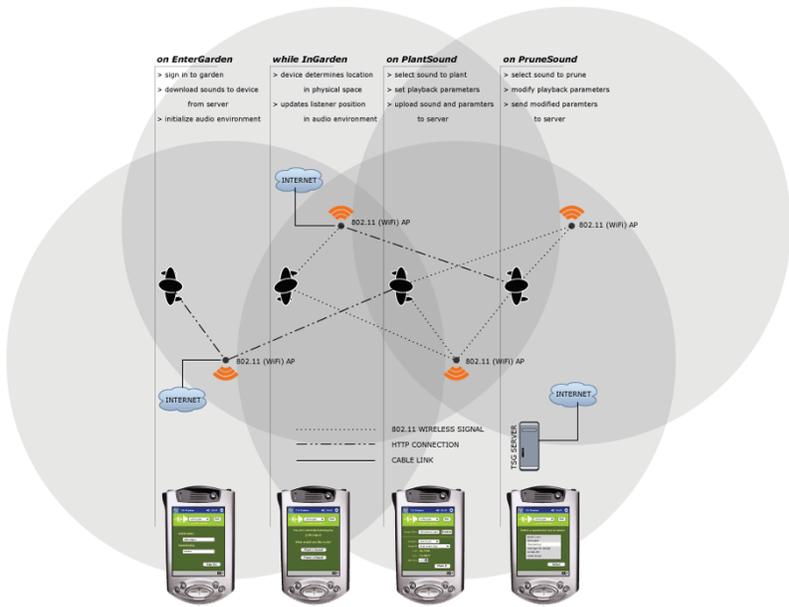


Fig. 30. Shepard illustrates the integration of wireless infrastructures that actuate physical environments.



Fig. 31. Aerial view of the sound garden. Shown are the sound signature 'planted' by participant of the TSG. This illustrates the cohesion of virtual space with the physical. The invisible network space manifests in the physical space.

(the sharing of favorite music files across a network connection), to articulate new terrain for social interaction (Shepard, 2007). The TSG project initiates and enriches physical spaces by first allowing the melding of social interactions, and also empowers the user of the space to be an active creator of his/her space and not just a passive entity.

The TSG project explores the concepts of social connectivity propagated by the barrier-less virtual environments expressed by sound. It illustrates the translation of the immaterial network fabric onto the physical urban fabric. As a result, the segmented physical fabric starts to transform, into a ubiquitous field of virtually barrier-less space where novel social interactions transpire. These technologically mediated physical environments activate new social and spatial interactions. This project demonstrates the correspondence of the virtual and the physical and how it bridges new connections between them. This manifests into a new type of physical-virtual environment. As a result, the immaterial networks may instigate a type of "immaterial" architecture.

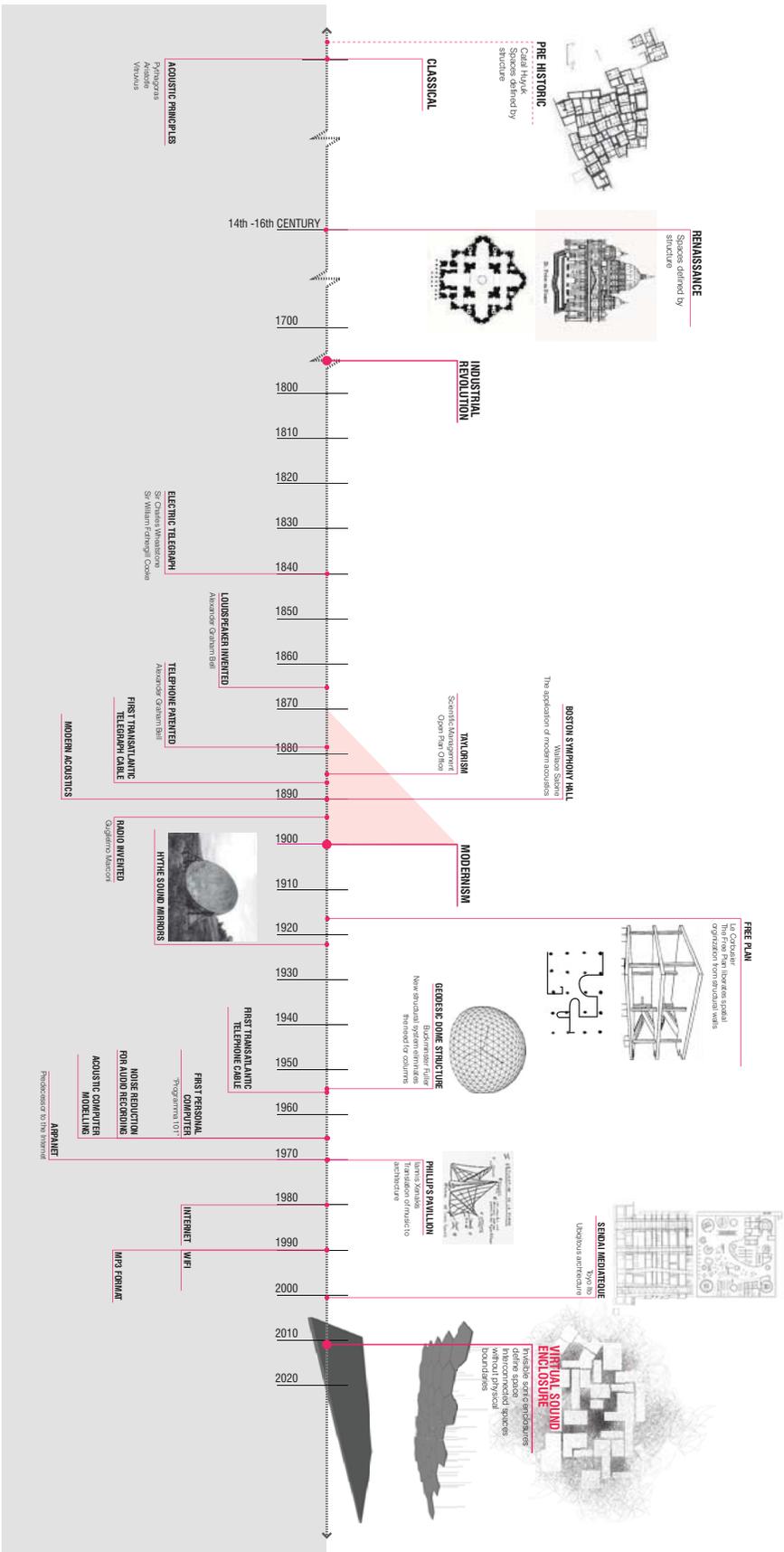


Fig. 32. Timeline denoting the architectural innovations that transpired in comparison to technological developments made in acoustics and telecommunications

## PERCEPTION OF SPACE

The phenomenological understanding of our environment has been one of the relying premise through which we have risen to become the dominant species of this planet. A highly developed aptitude towards perception and contemplation of the environment has protected us from the predators in the wild to the sound of on-coming traffic on a bustling city street. An amassed influx of empirical information gives us the ability to perceive the world around us, entailing us to not just be aware of our space but also our place within that space as it constantly encompasses our being (existence) (Ching, 1996)

“Through the volume of space, we see forms, hear sounds, feel breezes, smell the fragrance of flower gardens in bloom. It is a material substance like wood or stone. Yet it is an inherently formless vapour.”  
(Francis D. K. Ching, 1996)

Unlike the rationalist principles of modernism, phenomenology sanctions the method of contemplative consciousness of the individual experience through empirical means that engenders the faculty to navigate, orient and deliberate. In architecture, phenomenology has been a reflective subject of study since the idea was first influenced by Martin Heidegger . It not only defines the existence of a space based on sensory stimulants such as material substance, shape, texture, colour, and sound but also discloses our place within it. This understanding of phenomenology fastens into an ontological discussion as mentioned by Maurice Merleau-Ponty in 1945. Heavily influenced by phenomenologist Edmund Husserl's work, Merleau-Ponty's reveals the structure of perception where he denotes that first we perceive the world, then, we do philosophy,

“The perceived world is the always presupposed foundation of all rationality, all value and all existence. This thesis does not destroy either rationality or the absolute. It only tries to bring them down to earth.”  
(Maurice Merleau-Ponty, 1964)

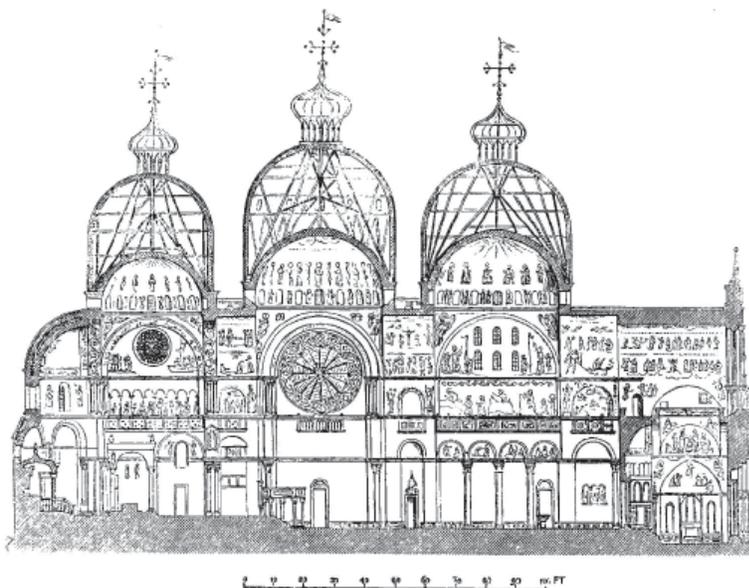
Merleau-Ponty hails the perceived world as the foundation of all existence, and all rationality. This idea brings into question the Cartesian and Euclidean rationality which laid its foundations from antiquity on rational architectural proportions (Melioli, 2005). A phenomenological perspective allows the conception of space

not only through quantitative exploration, but also through the experience of space. It relieves architecture from a rigid understanding of form and space to a more dynamic and flexible interpretation informed by societal experiential factors. Phenomenology, hence, expands architectural exploration and expression and brings architecture to its existential understanding. Pallasmaa: “architectural problems are far too complex and existential to be dealt with in a solely conceptualized and rational manner”. Phenomenologist, Edmund Husserl discusses eidetic intuition as he is concerned with physical analytic geometry. Husserl’s philosophies favour a non-metrical approach to geometry, hence leading towards a phenomenological approach to space. Early theories on the architecture mostly discussed strategies concerning formal expression of the built ‘object’ and seldom discussed the concept of spatial characteristics. It was only at the beginning of the 19th century did the discussion of space and spatial experience start to develop. Scholars such as August Schmarsow state,

“...Man imagines in the first place the space which surrounds him and not the physical objects which are supports of symbolic significance. All static or mechanical dispositions, as well as the materialization of the spatial envelope, are only means for realizing an idea which is vaguely felt or clearly imagined in architectural creation... Architecture is ‘art’ when the design of space clearly takes precedence over the design of the object. Spatial intention is the living soul of architectural creation” (Schmarsow, 1897)

Until recently, the architectural position on the phenomenological execution of space has been a product of physical form and volumes.

“As space begins to be captured, enclosed, molded, and organized by the elements of mass, architecture comes into being.” (Ching, 1996)



However, with the correct use of phenomenological inputs, designers can start to probe spaces that go beyond their formal Euclidean understanding, and in turn reveal more dynamic and fluid spaces. As sound exists indefinitely in any space (unlike light), it is the only constant phenomenon that defines space. Sound has a direct correlation with the perception of space. Sound bares the non-Euclidean geometry, projective geometry, projective space, as discussed by Matteo Melioli,

Fig. 33. Section of St. Mark's, Venice.

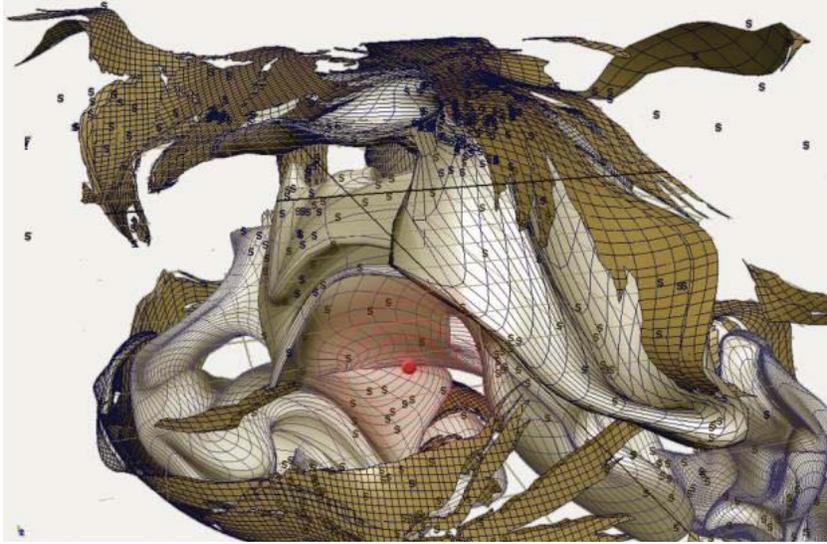


Fig. 34. Melioli visually maps the reverberation and echoes created by a sound source (red dot) placed in the basilica unveiling a formal expression of sound unique to that space.



Fig. 35. Formal expression of the soundscape of the church.

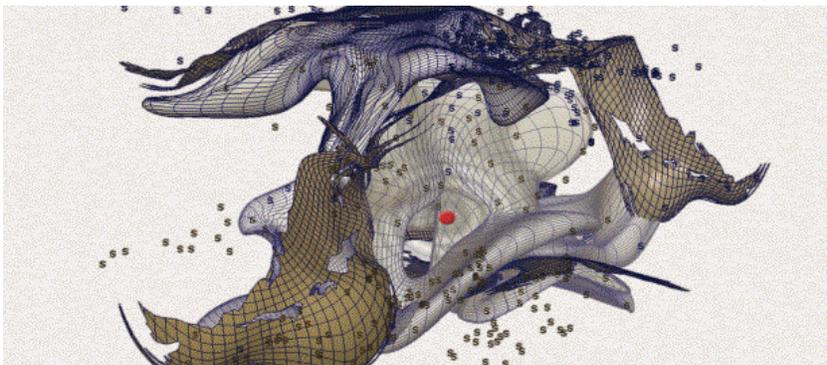


Fig. 36. With the material composition of the physical space omitted reveals "ghost spaces" that are invisible to the eye.

"Sound has therefore the power of deforming spatial perception, making space assume geometrical configurations that are complex and not linear, configurations of 'ghost' spaces extending beyond the physiological boundaries of our sensory perception" (Melioli, 2005)

So, if the physical elements that define form and volume were to be obscured or even eliminated, can we still perceive space? Traditionally, there has been an evident divide between the seen and the unseen in architecture. Melioli's work on the, Saint Mark's church in Venice (Figure 33), tries to examine the unseen phenomenon of echoes and reverberations in the Byzantine basilica and studies it visually. He maps the sounds reflecting off the stone walls, and through modeling software, he visualizes the interactions of the sound within the space (Figure 34). Hence, he reveals the unseen 'ghost' space which could only be heard. "Sound becomes the measure and scale of our perception modeling an intimate and vague space in our imagination" (Melioli, 2005). Sound has the power to reveal the invisible space and also has the power to create. Through this process of translating the immaterial phenomenological understanding into a visual expression, one can appreciate the impact sound has on the experience space. "Similar to how the ambiguity of a completely dark space is eliminated with the presence of light, Sound and the acoustics of a space also inform the user of a certain kind of space". Architect Juhani Pallasma (1996), who rejected the assumption of visual dominance, considered "sensory architecture as an umbrella theme that explicitly included aural architecture."

## Auditory Spatial Perception: Creating Space from Sound

Auditory spatial perception is the mind's ability to perceive space through sound. An amalgamation of aural sensory stimuli, personal history and cultural values reveal to the mind the spatial attributes of our environment through a mental process called auditory spatial awareness. Barry Blesser, a former professor at MIT and the inventor of the digital reverberation system, argues that auditory spatial awareness facilitates the mind to perceive space through complex cognitive processes that enables us to visualize space while allowing the mind to orient, navigate, and affect our consciousness of being in a space. As auditory spatial perception informs us of our surroundings it also "influences social behaviour, as some spaces emphasize aural privacy, and aggravate loneliness, while others reinforce social cohesion" (Blesser, 2006).

As one of the defining principles of architecture is the formulation of spaces that allow social cohesion and/or social isolation, sound proposes a dynamic material from which to compose space. A material, in the traditional sense of the word has an inherent prerequisite of being composed of physical matter. Sound however, is not matter. Sound is an immaterial pressure wave, audible to the human ear that enables the perception of space. Rather than designing space created by physical boundaries, aural phenomenological understanding provides the psycho-acoustic basis from which we can simulate virtual spaces. The manipulation of auditory stimuli, through the means of active acoustic systems, can create spatial experiences where physical space or materiality does not have to exist, hence, rendering effective phantom and illusory spaces. To achieve an illusory state of perception, the space needs to capture the aural stimuli and convey it to the user in a manner that creates the perception of space. As our environment interacts with us through a multitude of stimuli, our mind does not expend our complete attention to all stimuli at once; instead it distinguishes information from what is important and what is not to compose a mental depiction of a certain space (Nanda, 2006). We have a limited pool of attentional resources, and due to this limitation, interesting perceptual illusions may manifest (Spence, 2005).



Fig. 37. Auditory spatial perception. This diagram illustrates the possibility of creating illusory spaces driven by artificial inputs to the mind. This can be achieved through the use of electro acoustics.

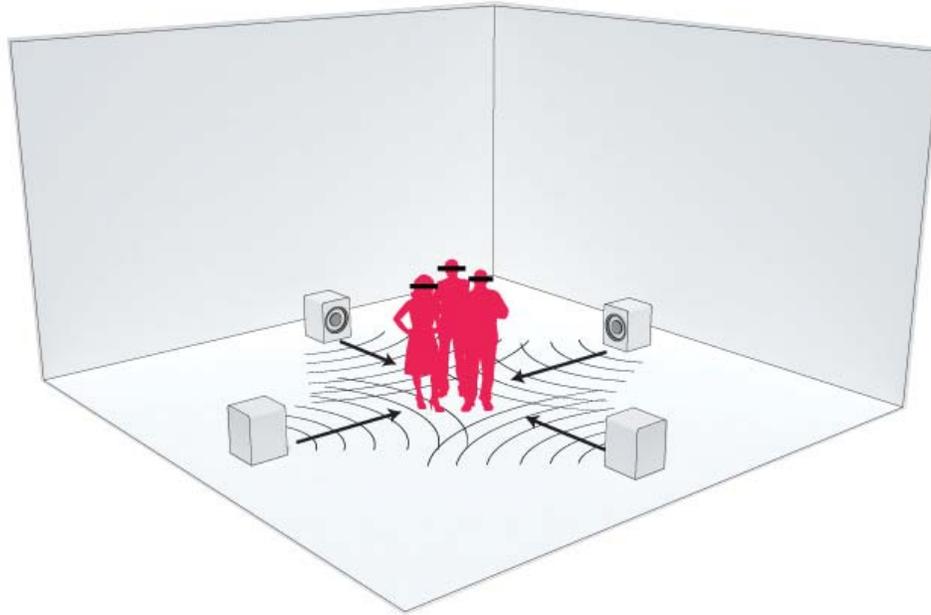


Fig. 38. Using surround sound, illusory spaces such as a Gothic cathedral, subway station, and a highway tunnel underpass were simulated that interacted with the sounds created by the participants of the space.

## EXPERIMENT 01

In order to test auditory spatial perception, a sound experiment was set up to relay only auditory stimuli to create the perception of space. A series of four loudspeakers were arranged around the participants to simulate an immersive spatial environment. The intent of the experiment was to harness the capacity of auditory spatial perception through the creation of illusory spaces by artificially altering the experience of the existing space by means of electroacoustics. The experiment was set up to sonically create the experience of specific types of iconic spaces, such as a cathedral, a subway station, and a highway tunnel underpass. The experiment was designed to not only project the soundscapes of these imaginary spaces, but also to be interactive with the participants. Hence, the space would also sonically respond to the user's activity such as their voices and other sounds generated as a result. For instance, if the user spoke in the simulated cathedral space it would sonically simulate their voice as it would be heard in a cathedral. Participants were blindfolded and brought in to a dark room to omit any visual sensory inputs that would otherwise inform the user of the pre-existing dimensions and materiality of the space. Without having any predisposition of the true image of the space, the participants were encouraged to freely perceive the space as informed by the auditory cues and soundscapes generated by the speakers. They were asked to stand at a specific point in the room and interact sonically with the space and each other in a candid manner. As the participants interacted with the simulated space they were led to perceive illusory spaces generated purely through auditory spatial perception. The participants were led to imagine an artificial space to have unique characteristics and identify the space in which they were standing in, without any visual stimuli. The participants were able to gauge their own presence in reference

to the simulated space. “When a space is exposed to full sonic illumination and you have sufficient cognitive skill to interpret the multiplicity of acoustic cues, you can aurally visualize passive acoustic objects and spatial geometry.” (Blesser, 2006)

\*\*SEE APPENDIX FOR AUDIO EXAMPLE

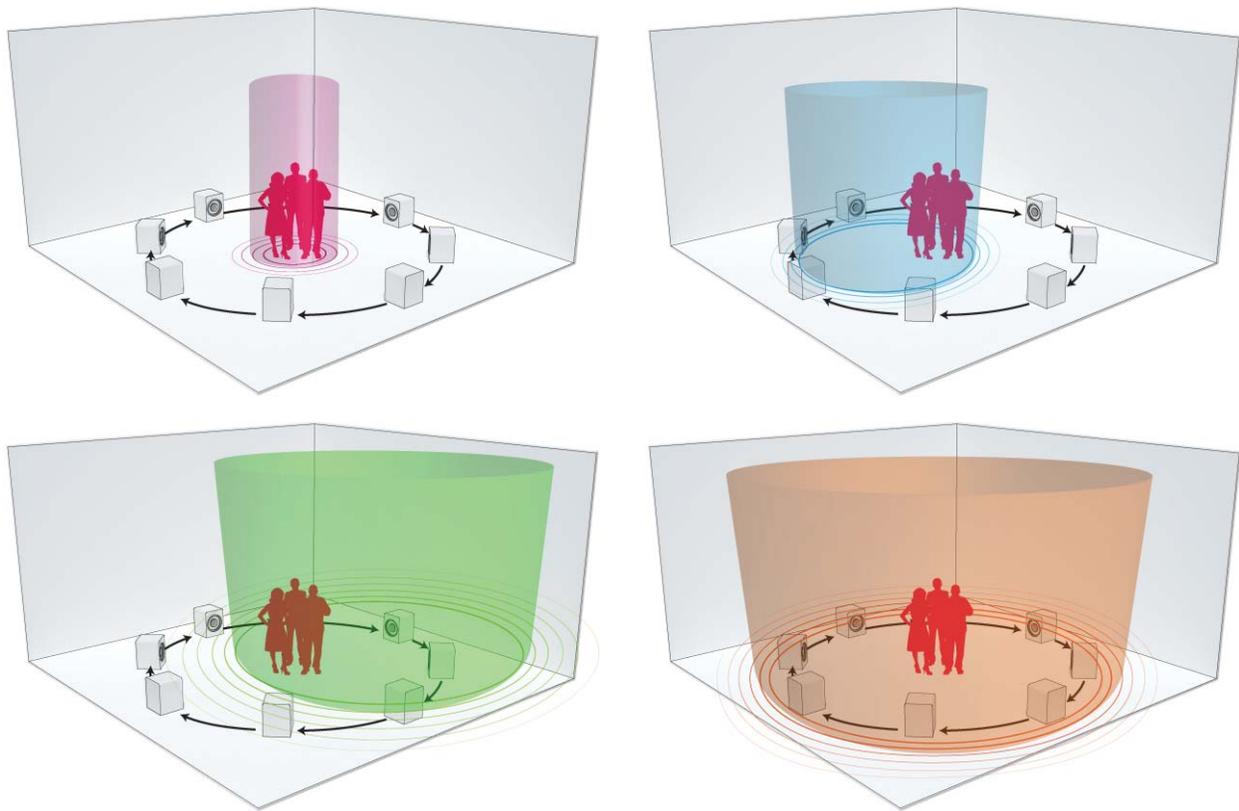


Fig. 39. The movement of sound at varying speeds and levels mapped various sizes of simulated spaces. The movement of sound was programmed to also simulate where the participant was standing in relation to the illusory space. While in reality the speakers remained stationary as only the auditory inputs simulated dynamic virtual spaces.

## EXPERIMENT 02

A subsidiary experiment was set up to observe how the sequenced movement of atonal sounds travelling through eight loudspeakers placed around the participant would reveal significant spatial understanding of the user's orientation, and location within a space solely through auditory spatial perception (Figure xx). The participants were lead into the experiment room without any visual cues to allow impartial perception of space created by the movement of sound. The programmed movement of sound simulated spaces of various sizes in relation to the static position of the participants. This sequenced movement of sound was able to inform the users of their approximate location within the simulated space. Experiential observations showed that sound can be used to invoke not just the sense of being in space, but also was able to inform the users of their approximate locations within the simulated space. For instance, the manner in which the sound traveled from

one speaker to the other at varying intensities of loudness and speed denoted the participant spatial proximity to the virtual sonic boundaries created by moving sound.

Given that through auditory spatial perception, we can perceive space; this suggests the possibility of composing spaces through the controlled manipulation of sonic events and aural inputs to the mind. Observations made from these exercises explain how sound can be developed as a medium to generate illusory spaces that transpire independent of physical boundaries through the appropriate execution of auditory stimuli. This is due to the mind only expending attentional resources to acquire information that informs orientation navigation, and invokes an active contemplative process of aesthetically defining a space. Therefore, sound can not only create the experience of being a space but also has the faculty to place the user within that space. Through our sensory perception we pay attention to what is important, thus, optimizing the efficiency of useful information that allows us to perceive space. This handicap can give designers a possibility of manipulating perception of space by controlling the input to the senses. If we design a place where the sensory input is fragmented then the user will be unable to form a cohesive real image and entail the generation of virtual sonic spaces. Through immaterial architecture we can create space.

\*\*SEE APPENDIX FOR AUDIO EXAMPLE

Drawing from these experiments, the VSE system is designed to created illusory spaces as induced by auditory spatial perception. With the controlled array of output from the speakers, a multitude of diverse spaces can be simulated. As the user perceives silence and other illusory aural environments, the Virtual Sonic Enclosure allows the composition of immaterial sonic enclosures within a noisy environment.

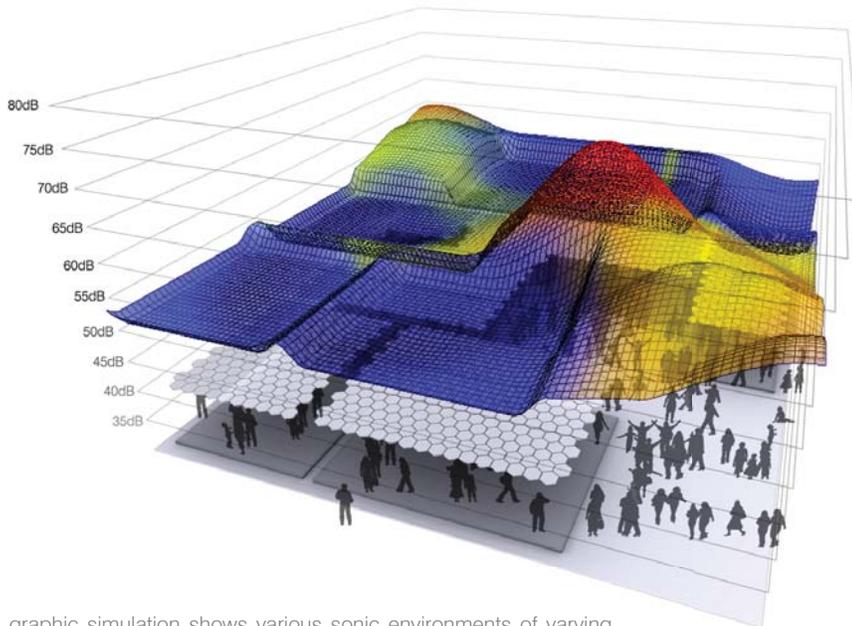


Fig. 40 This graphic simulation shows various sonic environments of varying acoustic intimacy can be generated through the VSE. With the use of parametric array loudspeakers, quite programs can be situated directly beside programs that require a louder threshold.

## MATERIALITY & IMMATERIALITY

“Can architecture be heard? Most people would probably say that architecture does not produce sound, it cannot be heard. But neither does it radiate light and yet it can be seen. We see the light it reflects and thereby gain an impression of form and materials. In the same way we hear the sounds it reflects and they, too, give us an impression of form and material.” (Steen Eiler Rasmussen, 1999 )

Materiality and form is an intrinsic part of architecture and acoustics. Since the writings of Vitruvius, materiality and form are discussed as an instrument for formulating spatial acoustics. Materiality plays a dominant role in the way sound is reflected, refracted and absorbed and hence informs the quality and perception of spatial sonics. In the Renaissance, Athanasius Kircher was one of the first to experiment with the sonic faculties of materiality and form as he discussed in his 1673 treatise – “Phonurgia Nova” (Magical Space of Sound and Silence). Later, as the modern sciences emerged, a scientific understanding of spatial acoustics, informed by materiality and form, initiated the designs of calculated acoustic chambers to house performance

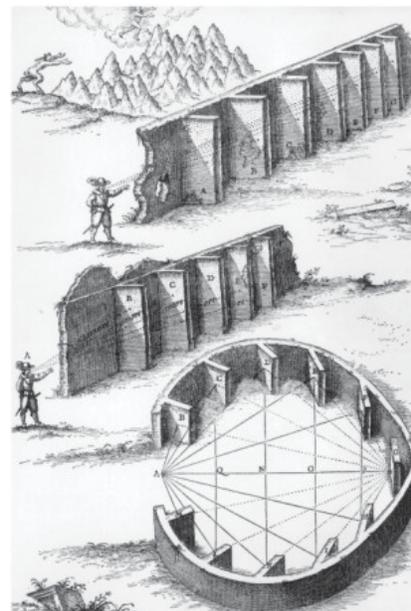


Fig. 41. Experiments by Kircher exploring echoes.



Fig. 42. Boston Symphony Hall, 1890.

Fig. 43. (Left). Anechoic Chamber.

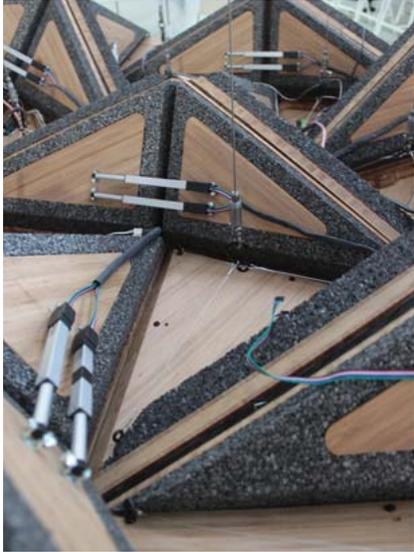


Fig. 44. Resonant Chamber, RVTR, 2011 is responsive acoustic installation.

spaces such as the Boston Symphony Hall designed by acoustician Wallace Sabine in 1890. The calculated positioning of materials allowed desired spatial acoustics attributes to emerge. Through the use of materials, complete control of sound was attained as it is evident in the design of an anechoic chamber where the sound absorbent material deadens all sonic energy to a state of complete silence. This state of silence is so extreme that one can listen to the pulse of their own heartbeat. Hence, materiality was used to acoustically distinguish between intimate quiet spaces and loud spaces with the use of acoustic walls and barriers. As spatial characteristics and functions have become increasingly diverse over the years, the interest in acoustically responsive application of materials and forms has emerged. The Resonant Chamber designed by RVTR in 2011 is a responsive acoustic element that deforms accordingly to achieve the desired perception of sound within an irresponsive space (Figure 44). Materiality and form also allow the development of metamaterials that can produce expressions such as the sonic sculpture designed by minimalist artist, Eusebio Sempere in the 20th century (Figure 45). Acoustic metamaterials can manipulate sound in space. The sculpture is a series of undulating stain-less steel tubes that alter sound frequencies as sound passes through it. Tests conducted by acoustic scientists Francisco Meseguer, revealed that the steel tubes were creating a “sonic band gap structure”. Derived from the sculpture,

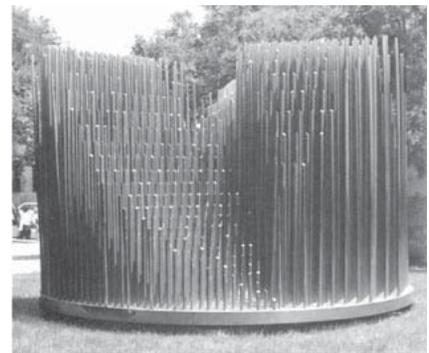


Fig. 45. Sonic sculpture by Eusebio Sempere

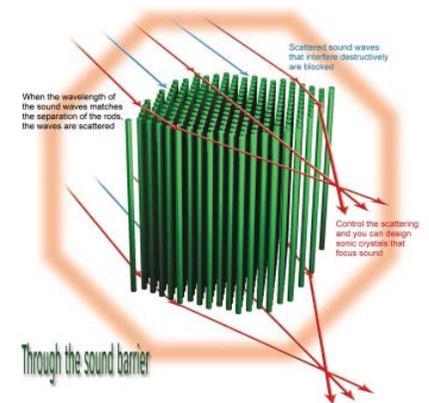


Fig. 46. Sonic metamaterial also known as sonic crystals.

Meseguer designed similarly calculated structures by manipulating the spacing and diameter of the rods to completely attenuate certain frequencies and even amplifying some and changing the acoustic properties of space. However, in the social structure of a network society where barrier and boundaries are becoming increasingly ephemeral, there is a need to discover ephemeral materials. Since sound is inherently ephemeral, its application can postulate generating transient spaces.



Fig. 47. Leitner uses the movement of sound to create spaces of sound.

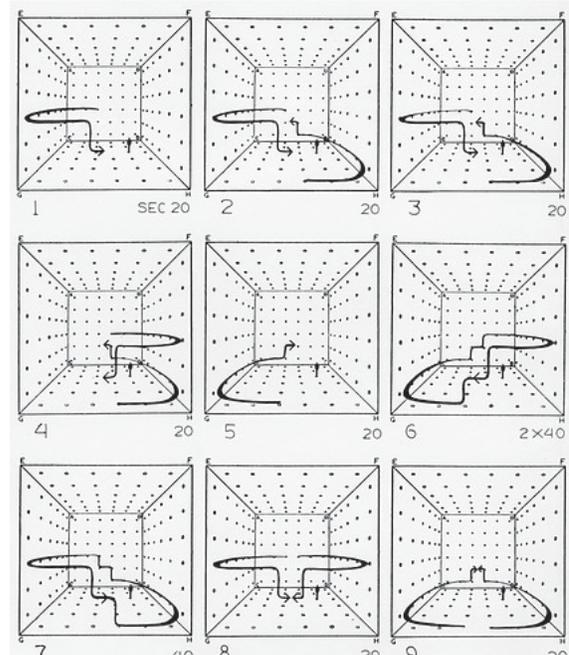


Fig. 48. "Sound Cube", Bernhard Leitner. The movement of sound around a body creates spaces defined by sound.

An account of using sound as a material to construct ephemeral spaces is the work of composer/ architect Bernhard Leitner as he describes sound as a "plastic sculptural medium" (Leitner 2011). Leitner's work has evolved over 30 years that employs the use of electroacoustic techniques of moving sound through a series of loudspeakers to create space. The "Ton-Wurfel" (Sound Cube) exploits the perceptive power of the mind to perceive the movement of sound around a body to compose space (Figure 48). Other applications of sound as a constructive material are the works of composer and sound installation artist, Robin Minard. As a composer, Robin Minard's work explores the architectural spatial attributes of sound, as he 'composes' spaces from sound. In sound installation art, Minard explores the quality of relationships between audio, visual and/or architectural elements. Minard describes his compositions to be non-narrative music.

"In non-narrative music, or sound art, the emphasis is placed in the acoustic and psychoacoustic principles rather than the traditional musical concepts. These sounds then start to take on new meaning as the art (sound) is dictated by the influence of sound elements on spatial perception rather than the listener's perception of a musical narrative or musical syntax" (Minard, 2000)

In his non-narrative compositions, select frequencies of sound projected through a series of loudspeakers

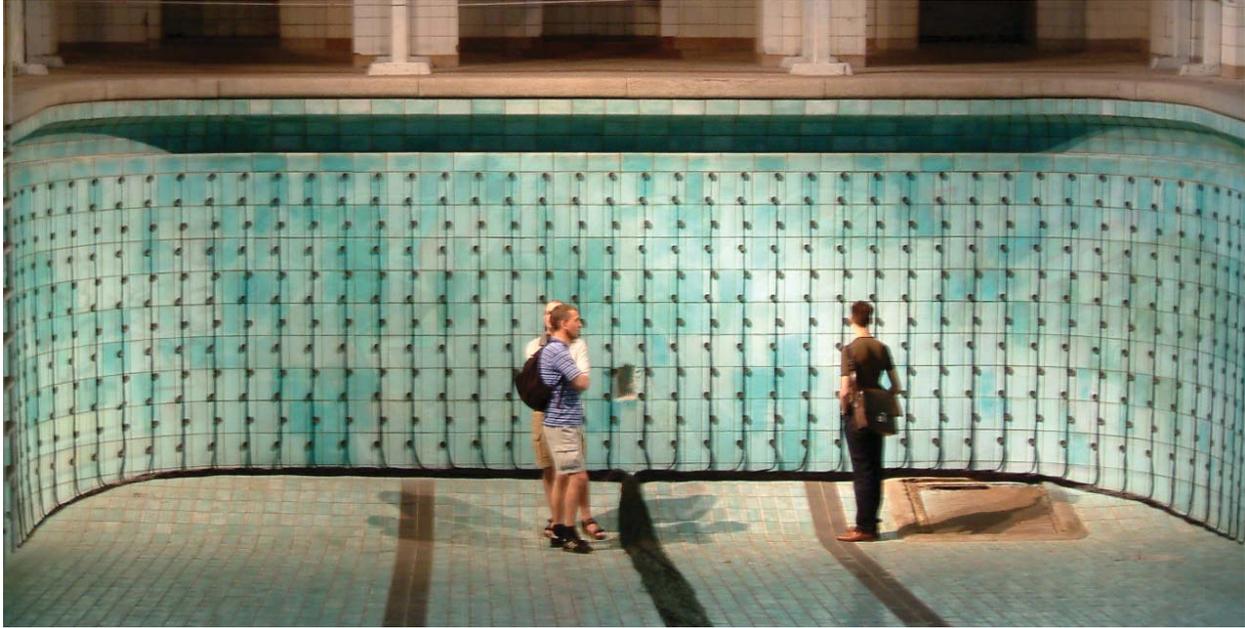


Fig. 49. (Top) "SoundBits" By Robin Minard



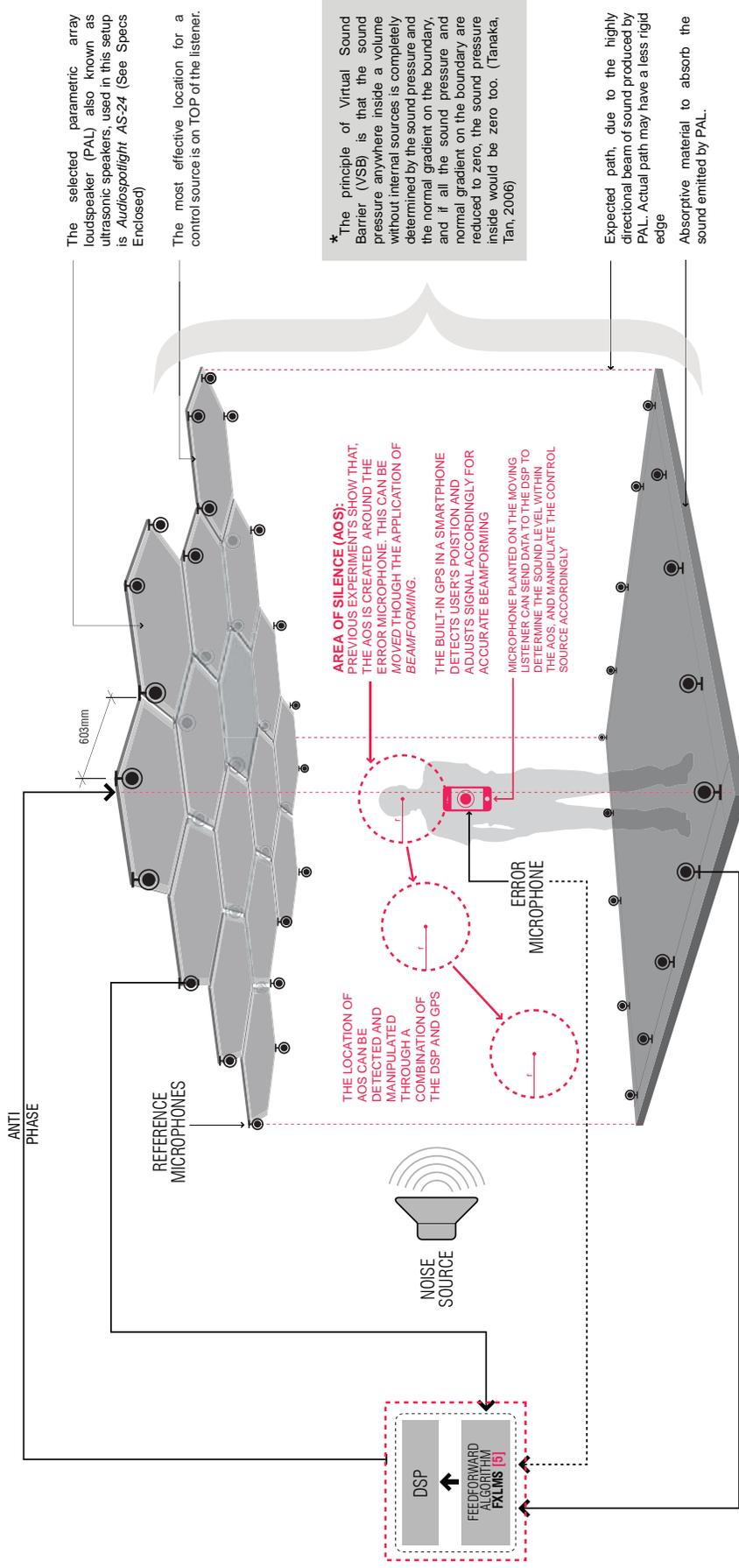
Fig. 50. "SoundBits" Placement of speakers that add to the "spatial timbre"

give the space its "spatial timbre" that alters the perception of space to be volumetrically larger or smaller. Spatial timbre is the acoustical character of a certain space. For instance, a church has a nostalgic spatial timbre that the user refers to when he/she experiences it. This consciously or sub-consciously denotes the character of the church to be cold, hard and grand (Minard. 2000).

Minard describes his work as ephemeral art, where it is composed to be used for transient spaces, responding to contemporary spatial interpretations. "Ephemeral works of art embody a perpetual state of metamorphosis; time very literally defines the truly ephemeral work of art" (Minard, 2000). As Minard explains, the twentieth century modernism has transformed subject into material form as spaces need to shift from this model to a transitory state.

Drawing from these examples, the Virtual Sound Enclosure employs similar techniques to generate transient spaces that respond to contemporary spatial conditions. Shaping sound in space through the VSE demonstrates the application of sound (an immaterial physical phenomenon) as a medium to compose immaterial architecture.

# VIRTUAL SONIC ENCLOSURE



The selected parametric array loudspeaker (PAL) also known as ultrasonic speakers, used in this setup is *Audiospotlight AS-24* (See Specs Enclosed)

The most effective location for a control source is on TOP of the listener.

\* The principle of Virtual Sound Barrier (VSB) is that the sound pressure anywhere inside a volume without internal sources is completely determined by the sound pressure and the normal gradient on the boundary, and if all the sound pressure and normal gradient on the boundary are reduced to zero, the sound pressure inside would be zero too. (Tanaka, Tan, 2006)

Expected path, due to the highly directional beam of sound produced by PAL. Actual path may have a less rigid edge

Absorptive material to absorb the sound emitted by PAL.

Fig. 51. Virtual Sonic Enclosure Schematic

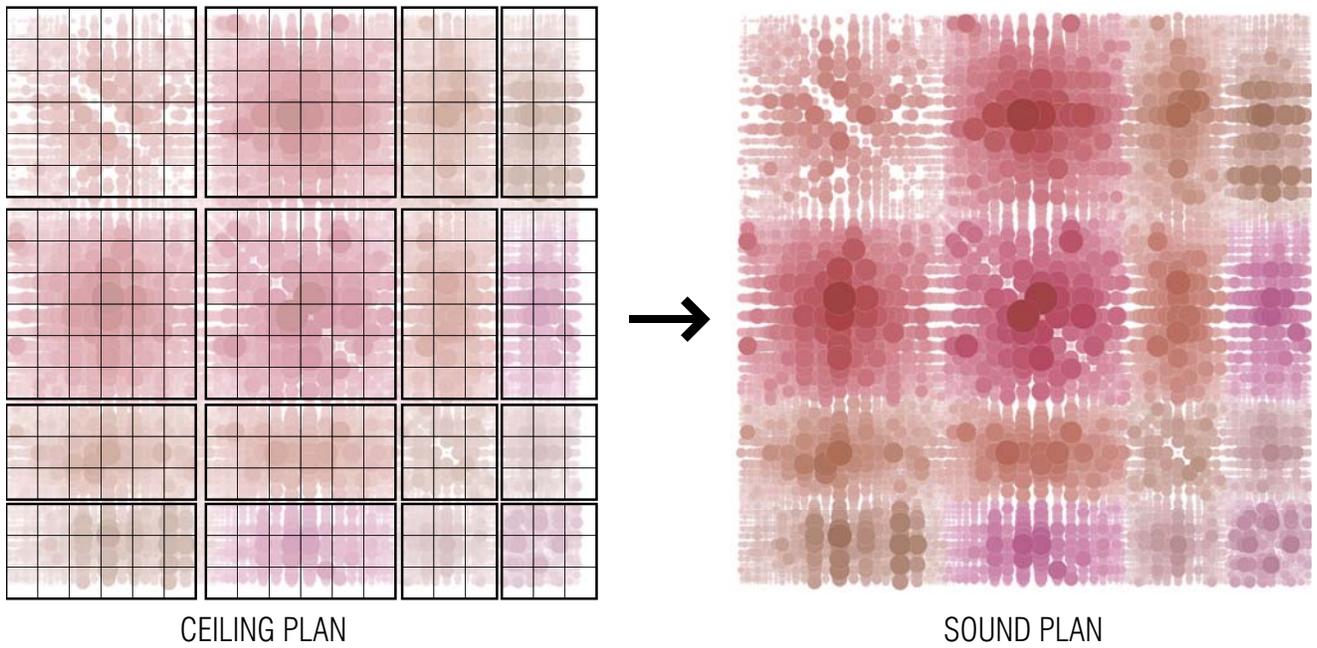
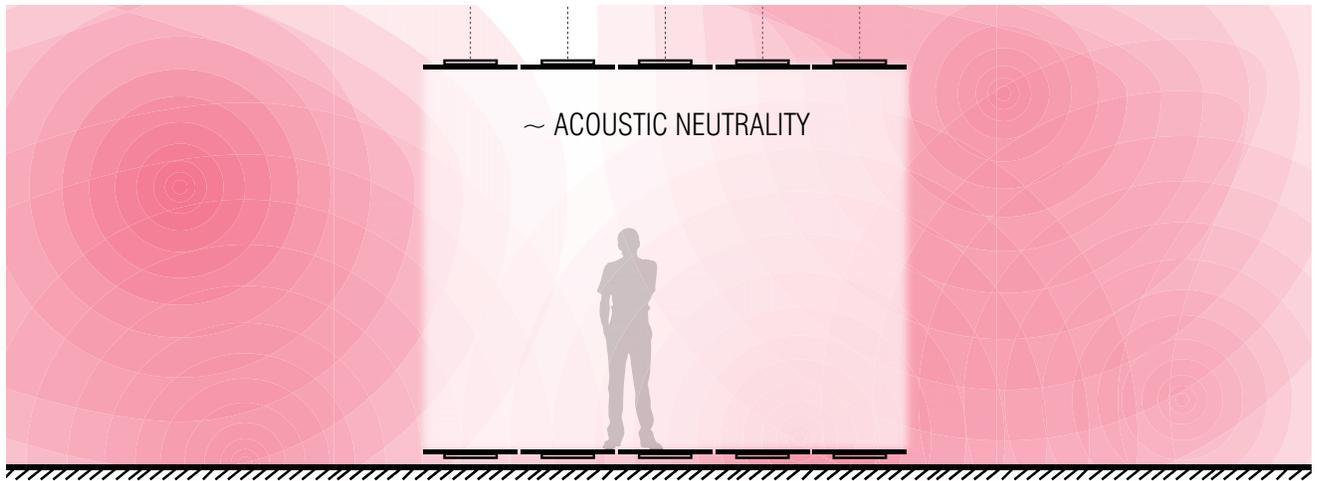


Fig. 52. The VSE can be expressed into spaces created by sound. Each space has its own aural characteristics independent of any physical partitions.

The design intent of the Virtual Sound Enclosure (VSE) is to generate immaterial sonic voids within a noisy environment. Traditionally, acoustic technologies relied on the application of physical materials that diffuse and absorb sound. This approach however, limits the space to its physical and material confines. By employing electroacoustic techniques there is potential to create illusory spaces. The main principle driving the VSE technology is the modified application of active noise control or active noise cancellation (ANC) based on the theory that if the “sound pressure anywhere inside a volume without internal sources (sound sources) is completely determined by the sound pressure and the normal gradient on the boundary, and if all the sound pressure and normal gradient on the boundary are reduced to zero, the sound pressure inside would be zero too” (Qui, Zou, Rao, 2009).

## ACTIVE NOISE CANCELLATION

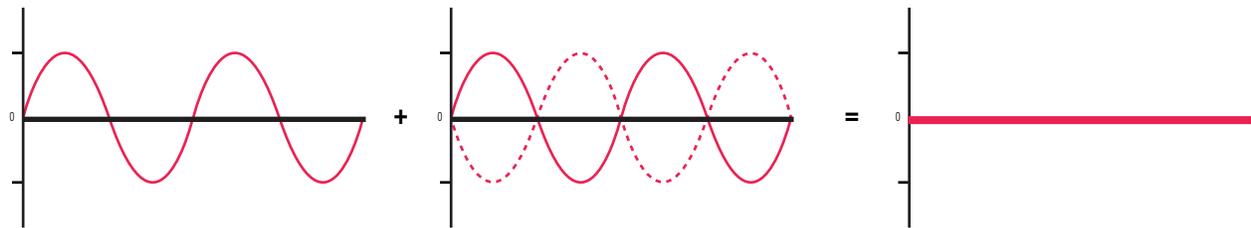


Fig. 53. Basic principle of ANC. When anti-noise is added to the original sound the resultant wave is zero.

The aim of ANC is the attenuation of unwanted noise through the electroacoustic manipulation of sound signals emitted by a control source. The mechanics of sound can be equated to a pressure wave that oscillates between compression and rarefaction phases (Figure. 53). An ANC system is controlled by a secondary transducer (control source) that emits an 180 degree inverted phase, or “anti-noise” of the unwanted sound (primary sound source). The waves combine to form a resultant wave, in a process called interference. Subsequently, the anti-noise cancels out the unwanted sound in an effect known as phase cancellation. The consequential sound wave is thus perceived to be inaudible to the human ear. For effective attenuation, the inverted control signals emitted by the secondary sound source must be directly proportional to the amplitude and frequencies of the unwanted sound source. The transducer emitting the cancellation signal may be located at the location where sound attenuation is wanted, for instance, the user’s ear. Conventional uses of ANC can be seen in aircraft cockpits, and more commercially known to be applied in noise-cancelling headphones. Since these applications are confined within a small space, simple attenuation is possible.

### A simple single channel ANC system consists of:

- A reference microphone sensor to sample the disturbance to be cancelled.
- An electronic control system to process the reference signal and generate the control signal. With the increase in computer processing power most ANC systems today are based on digital signal processors (DSP) rather than the analog system.
- A loudspeaker (control source) dictated by the control signal to generate the cancelling disturbance
- And an error microphone to provide the controller with information so that it can adjust itself to minimise the resulting sound field.

Theoretically the application of ANC demonstrates the full attenuation of all the frequencies as shown in Figure 53. In practicality, limitation posed by conventional control sources and processing capacity makes it difficult to achieve three-dimensional sonic attenuation. Conventional ANC systems are typically limited to lower frequencies ranging approximately below 500 Hz (Hansen, 2001). Though ANC gives the designer the ability to manipulate the sonic environment through active sound signals, thus far, it has been limited to the attenuation of only low frequencies. Achieving noise control at higher frequencies such as the human voice, ambient soundscapes, and etc., pose some technical difficulties that hinder its application. For instance, more complex vibrations and soundscapes require powerful processing capacity prompted by higher sampling rates. Additionally, conventional loudspeaker technologies used for control sources propagate sound omnidirectionally. This is helpful for attenuating low frequencies, however, due to high directionality and shorter wavelengths, higher frequencies are not able to be attenuated unless controlled by an array of control sources. Due to these limitations, ANC systems are fairly successful when applied in smaller confines such



Fig. 54. Cement plant. Installation of ANC silencer.

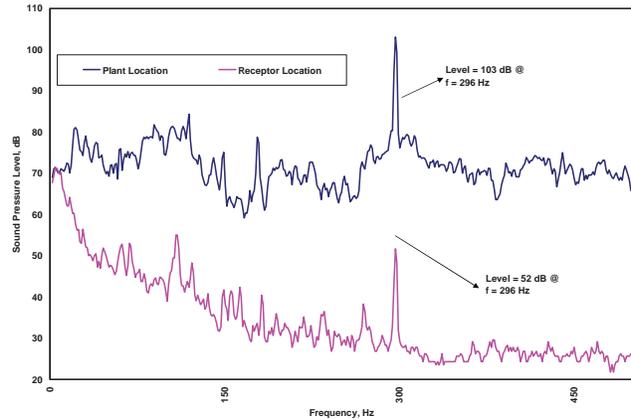


Fig. 55. Comparison of noise at plant location and receptor location

as mechanical ducts. A project conducted for the noise reduction from a dust collector centrifugal fan of a cement plant in Northern USA by Professor Ramani Ramakrishnan, and Werner Richardz, demonstrates a successful application of ANC for a mechanical systems (Figure 54). The fan produced a strong blade passing tone at 296Hz which could be heard a kilometer away in a dense residential area (Figure 55). Responding to the complaints of the residents, Ramakrishnan and Richardz designed an active noise control system to attenuate the invasive tonal noise of the fan which was heard in the band of 315Hz at 103dB in the residential area. The fan was fitted with a conventional dissipative silencer interposed between the sensing microphones and conventional loudspeakers. Unlike random noise, mechanical noise is usually at low frequencies. Hence, the uses of conventional loudspeaker control sources provide a viable solution for the attenuation of low frequencies. Since mechanical sounds are predictable and consistent, this permits the application of a simple feedback or feedforward system. However, for the attenuation of complex noise

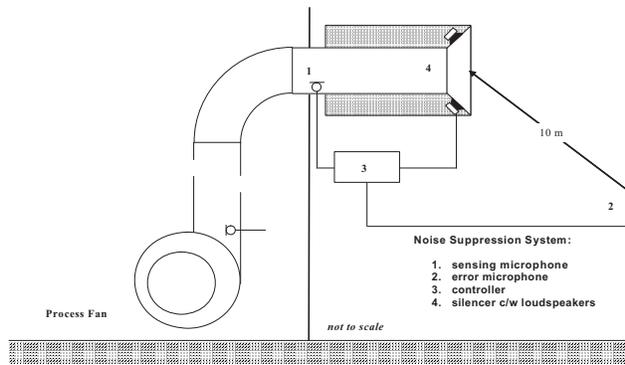


Fig. 56. ANC setup at the plant.

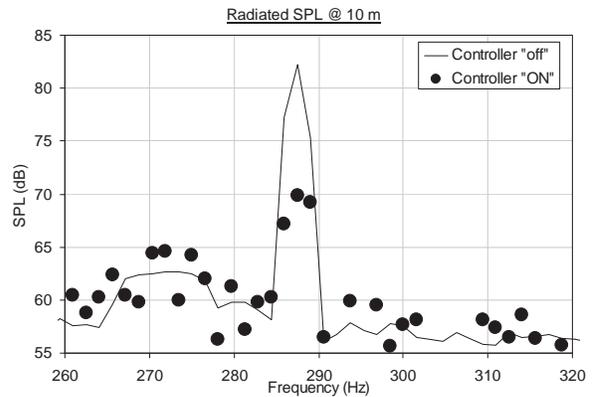


Fig. 57. Performance of the ANC system.

environments a hybrid of feedback and feedforward system must be applied. For the centrifugal fan ANC system, “the control source was configured to operate in a feedforward mode wherein the sensing microphones and phase and amplitude adjustments are made based on feedback from the error microphone”, (Ramakrishnan, Richardz. 2005). The designed ANC system proved to provide 12 dB reduction of the invasive blade tone as shown in Figure 57. In the case of the proposed Virtual Sonic Enclosure, the sound intended to be attenuated can range from simple repetitive atonal sounds to complex random noise. Thus, taking into account the limitations posed by conventional methods of ANC this thesis proposes a novel modification to achieve greater attenuation of higher frequencies while generating zone(s) of silence independent of any physical confines by employing the use of parametric array loudspeakers.

## PARAMETRIC ARRAY LOUDSPEAKERS

Conventional loudspeakers are very inefficient as they propagate sound omni-directionally. This can be useful in attenuating low frequencies, but has been proven to be ineffective against higher frequencies. In order to alleviate this limitation, this thesis proposes the use of parametric array loudspeakers (PAL) developed by MIT researcher, Joseph Pompeii (Figure 58). Unlike conventional loudspeakers, the PAL does not emit sound omni-directionally, rather it emit beams of sound similar to a laser. Pompeii uses airborne ultrasonic sound to generate audible sound beams (Pompeii, 1999). The PAL exploits an effect known as self-demodulation. Self-demodulation occurs when nonlinearities of a compressible medium (such as water or air) cause high frequency wave components to interact. The interaction between the ultrasonic frequencies produces resultant audible frequencies. Similar to the process of AM demodulation the ultrasonic frequencies act as carrier waves of the audible frequencies (Figure 60). Another such exploration was conducted by Woody Norris, who explains the concept of using the nonlinearity of air to produce highly directional audible sound. This is also known as the Tartini effect. When two ultrasonic sound frequencies go in and out of phase they produce a demodulated audible beat. With the correct ultrasonic frequencies being produced, it is possible to create highly directional audible sound.



Fig. 58 Audio Spotlight AS-16, parametric array loudspeaker.

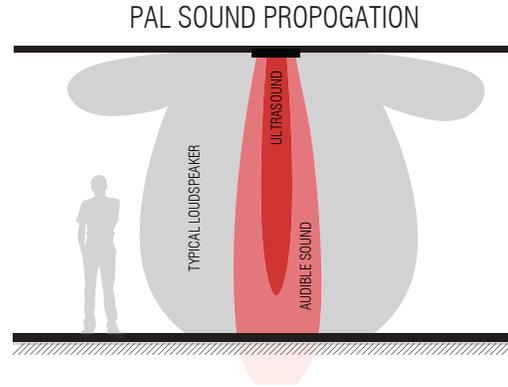
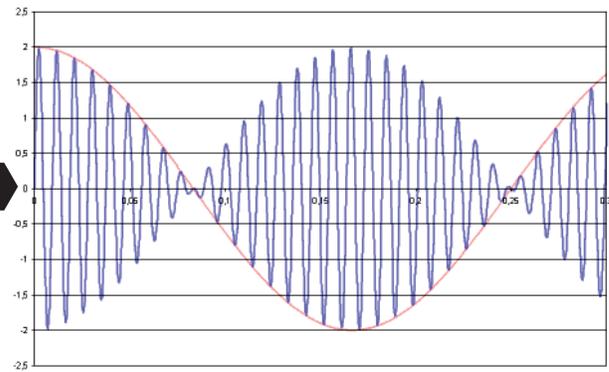
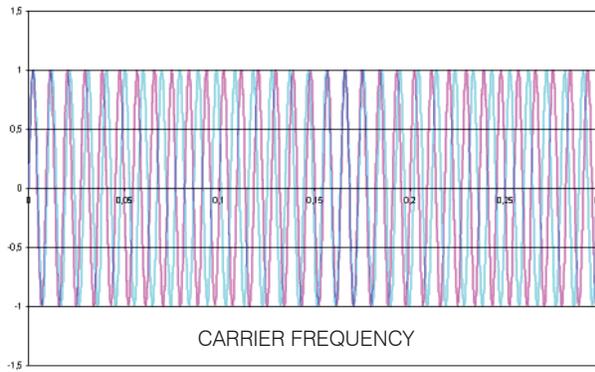
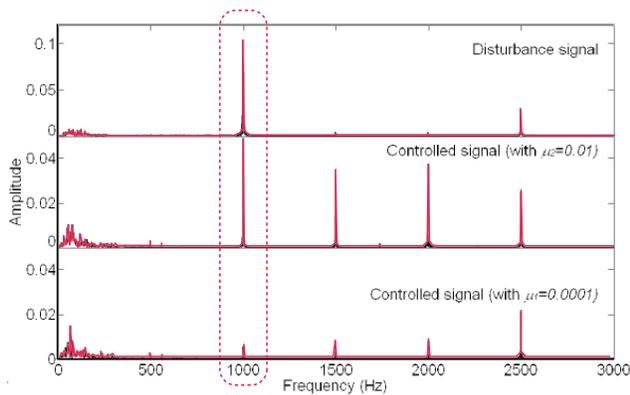


Fig. 59. Comparison of sound propagation of a conventional loudspeakers and the PAL. The PAL emits high amplitude ultrasonic waves which demodulate into directional audible sound due to non-linear interaction with the medium through which they propagate.

Fig. 60. (Below) AM demodulation.

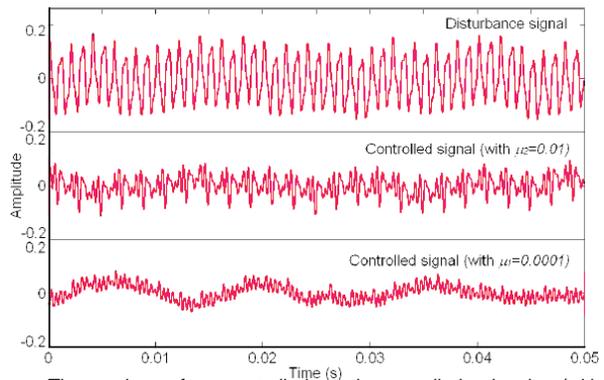


This beam like propagation of sound creates local zones of sound in the direction the PAL is facing. By using PAL instead of conventional speakers higher frequencies can be attenuated in an ANC system (Tan, Tanaka, 2006). Figures 61 and 62 express the active noise control performance through the use of PAL.



Uncontrolled and controlled signals in frequency domain (with  $\mu_1=0.0001$  and  $\mu_2=0.01$ )  
 $\mu$ =filter coefficient  $\rightarrow$  "feedforward" algorithm  $\rightarrow$  FXLMS

Fig. 61. The graph indicates the simulated results of the cancellation of higher frequencies facilitated by the use of parametric array loudspeakers.



Time-series of uncontrolled and controlled signals (with  $\mu_1=0.0001$  and  $\mu_2=0.01$ )

Fig. 62. The graph indicates the simulated results of the performance of active noise cancellation using PAL. The simulated controlled signals are greatly reduced from the initial disturbance signal.

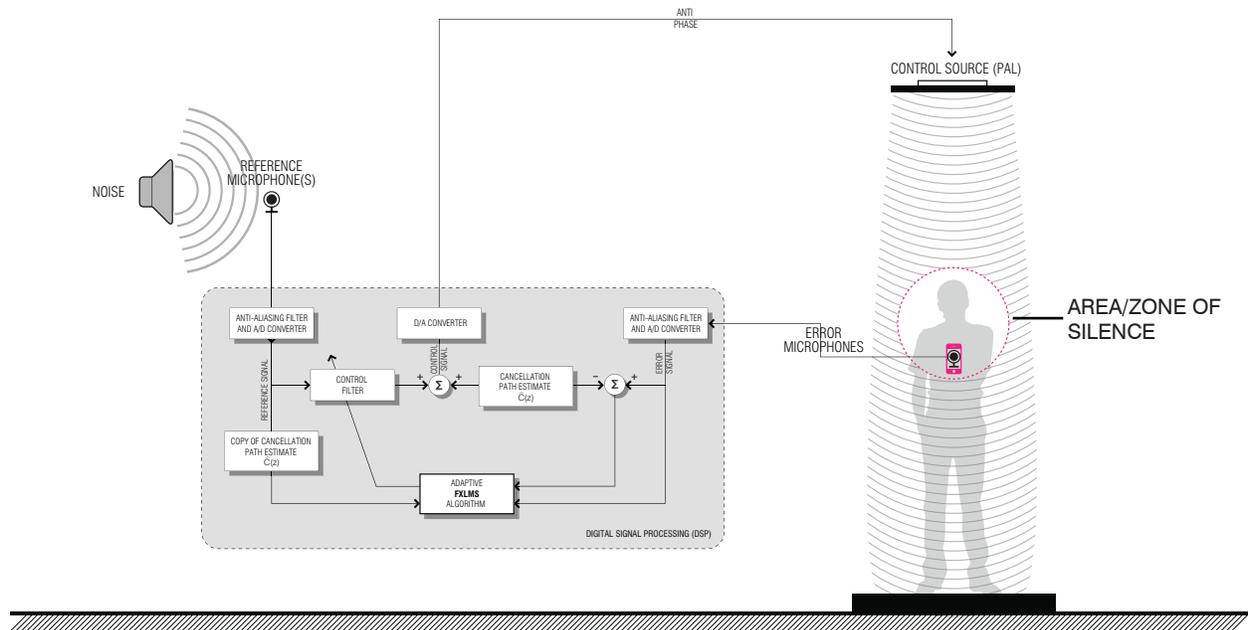


Fig. 63. Simple DSP configuration based on FXLMS algorithm for the VSE.

## DIGITAL SIGNAL PROCESSING

Though the science seems simple enough in theory, the practical application of ANC requires complex algorithms to compute the control signals needed to attenuate the unwanted sound. The control signals emitted by the secondary sound source must be directly proportional in terms of amplitude and frequency, while adapting to changing sonic inputs from the primary sound source. For this reason adaptive algorithms are processed through a digital signal processor (Figure 63). The adaptive algorithm used for the VSE is filter-x Least Mean Square (FXLMS) (See Appendix). This project also takes into account for the feedforward, and feedback system. Since the VSE is achieved through a ubiquitous plane of PAL control sources we need to apply a multichannel system as illustrated in Figure 64.

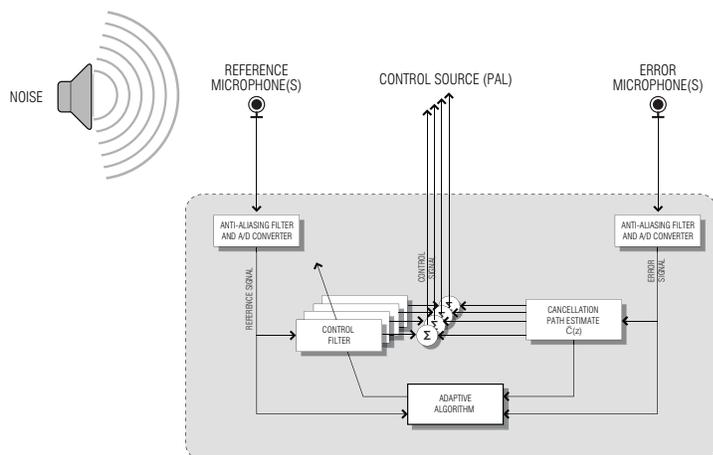


Fig. 64. Multi-channel DSP configuration

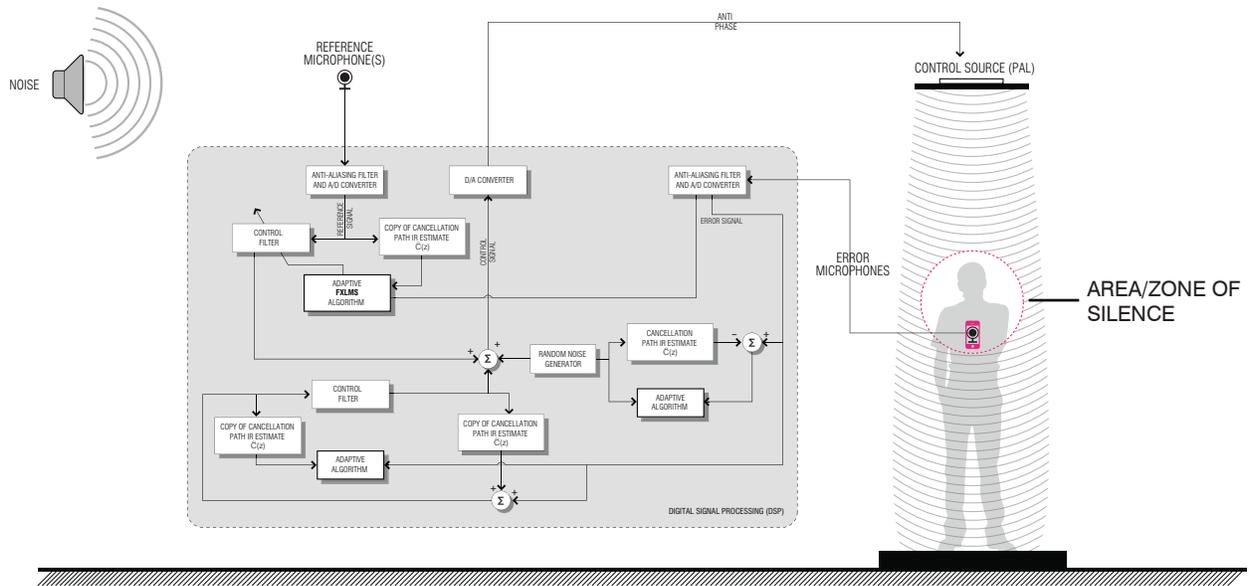


Fig. 65. This digital control system uses a combination of feedforward and feedback mode to achieve optimize the control signal.

More powerful control signal processors may help alleviate the technical limitations by extending the range of attenuation to higher frequencies and multichannel systems. As integrated microprocessors dedicated for signal processing have become more feasible and faster the potential for the proposed active noise cancellation system is highly plausible as shown by the function of the VSE. As random noise carries many frequencies that need to be picked up by the sensing microphones and processed accordingly the possible use of Fast Fourier Transform hardware (FFT) can be applied. The FFT is an adaptive algorithm hardware that processes individual frequency bins. The frequency bins are then amalgamated using an Inverse Fast Fourier Transform (IFFT) to provide the control signal. Through this process, significant improvement in the convergence rate can be achieved resulting in successful ANC for noise ranging in different frequencies. Figure 66. shows the control system schematic for the integration of FFT for frequency based control.

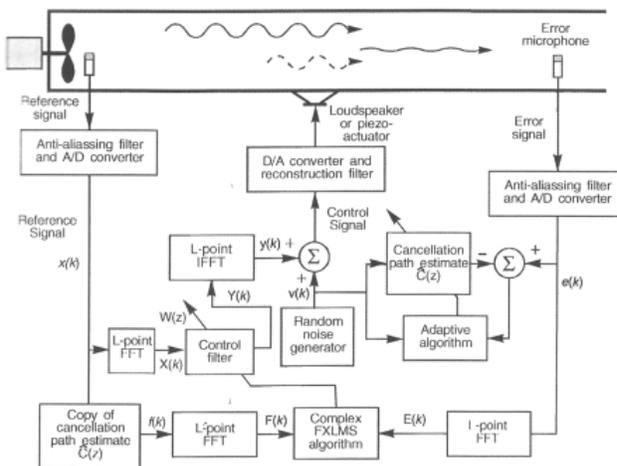


Fig. 66. Single channel DSP configuration with FFT integration.



Fig. 67. With the integration of VSE, sonically diverse space can be defined independent of physical barriers.



Fig. 68. The elimination of barriers from spaces, engender new relationships in collaborative spaces such as a studio/office.

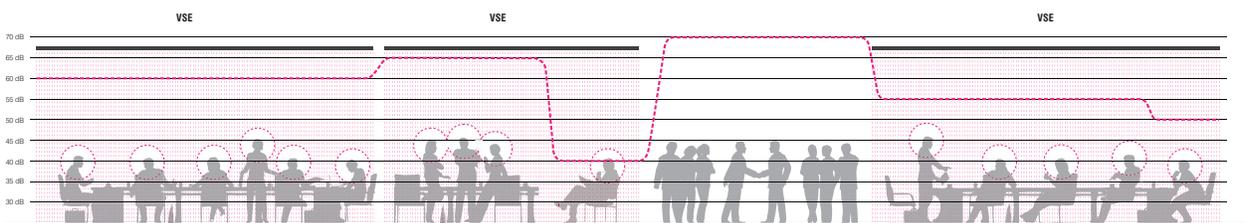


Fig. 69. Virtual sonic enclosures allow spaces of interaction on a ubiquitous plane of varying programs.



Fig 70. Spaces generated by the application of VSE

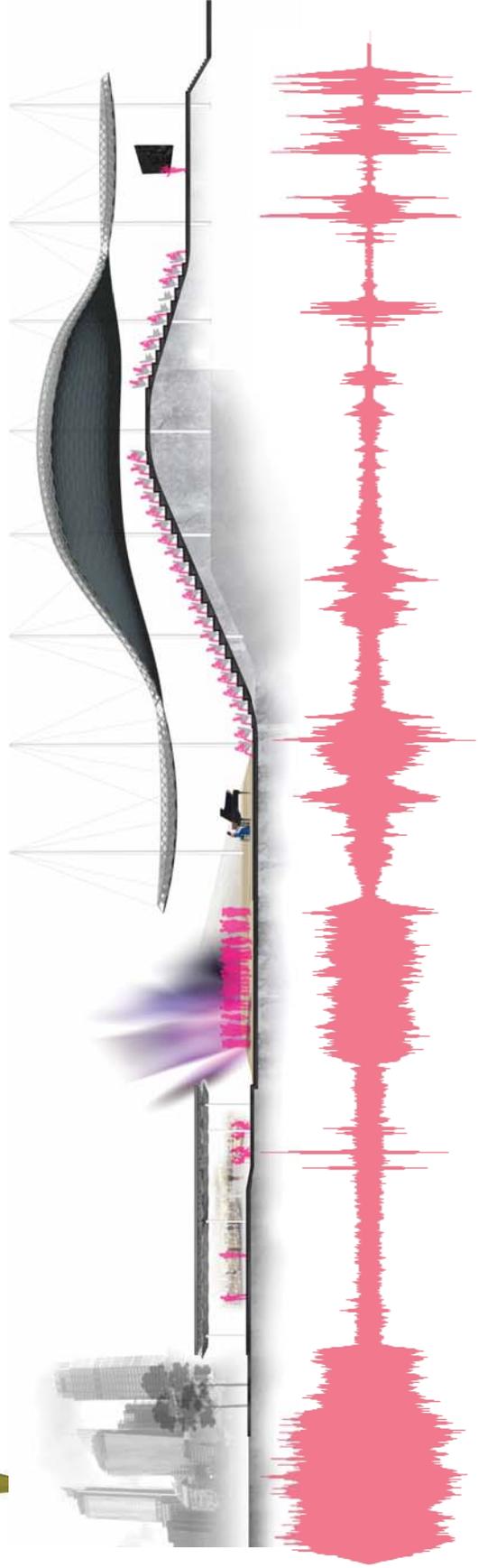


Fig 71. VSE Experiential Section

## CONCLUSION

The Facebook revolution of the 2011 Arab Spring illustrates the emergence of a network society actuated by a barrier-less space of the virtual world. With immaterial wireless networks driving cities and civilizations the masses are connected regardless of any physical boundary or border. The dissolution of the boundaries and barriers initiates the diffusion of sociocultural paradigms. As ideas and people start to interchange, a new prosperous society can emerge. With the destruction of the Berlin Wall, a barrier erected to metaphorically and literally hinder ideas and society brought upon a new age of social and cultural cohesion and understanding. To represent this condition, architecture must explore ways to create weak and ephemeral 'filters' that enable the intersection of programs and spaces that allow for seamless spatial and cultural osmosis, revealing novel spatial and programmatic possibilities.

In light of the changing urban conditions, this thesis proposes a system of interconnected spaces and programs, without the use of physical boundaries. Boundaries defined by filters of sound. The Virtual Sonic Enclosure is a system where sound is used to create immaterial enclosures of silence that allow the interpenetration of diverse spaces and programs. As architecture actuated by sound there is a new potential for form, program and space.

Expressed in this thesis are potential applications of the immaterial sound enclosures, however, in its current state the VSE presents some technical and architectural limitations. Technically, with the current processing capacity and power needed to generate such large fields of sonic spaces within dynamic and complex noisy environment is very difficult to achieve. As random sounds must be calculated and relayed through control sources without delay, it poses a difficult but not impossible challenge. For now, such enclosures can only be simulated in laboratories with highly sophisticated equipment. However, with the exponential advances being developed in processor technology, such large scale applications may become a reality in the near future. Architecturally, the proposed VSE is a discourse between the tangible and the intangible. It allows a new way

of constructing spaces that require varying degrees of aural intimacy, however this can be combined with other elements of architecture to generate a new types of architectural expressions. Walls and partition will have new meanings and applications. The spatial organization of space will no longer be constrained to materiality as this thesis suggests, since sound can be employed as an immaterial medium for spatial definition. With a new tool in arsenal of design, what architectural possibilities can arise from the application of immaterial sonic enclosures? Since visual and physical cues that define space dematerialize, what spatial characteristics are generated by aural cues?

By utilizing the smartphone as a sensor to generate a zone of silence and locate the user's position, architecture starts to be mediated by the active participation of the user activity. Networks and connections between peoples and communities would no longer manifest only in the virtual space but would also start to translate into the physical world. The transparency achieved by the removal of physical partitions and boundaries would start to encourage the interconnection of not only spaces and programs, but consequently the interconnection of ideas, people and cultures of the 21th century.

Hence, this thesis is an experiment towards reducing architecture to its least common measure. It seeks to establish permeable and invisible thresholds sound between juxtaposed spaces that activate life. What elements in architecture can exist independently of the other? For instance, can the omission of visual stimuli convey the clarity or even enhance perception of space? Or would the muting of tangible elements in architecture such as walls and barriers heighten the awareness of ones surroundings? How much further can architects strip away at the conformist elements that have defined the main principles of architecture to still be considered architecture?

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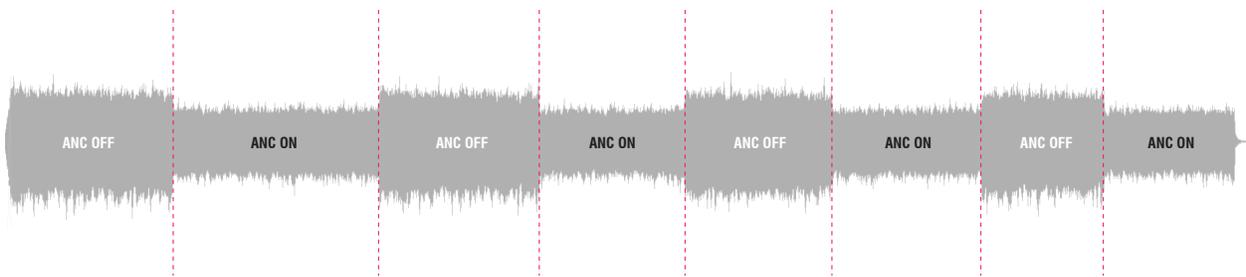
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## APPENDIX

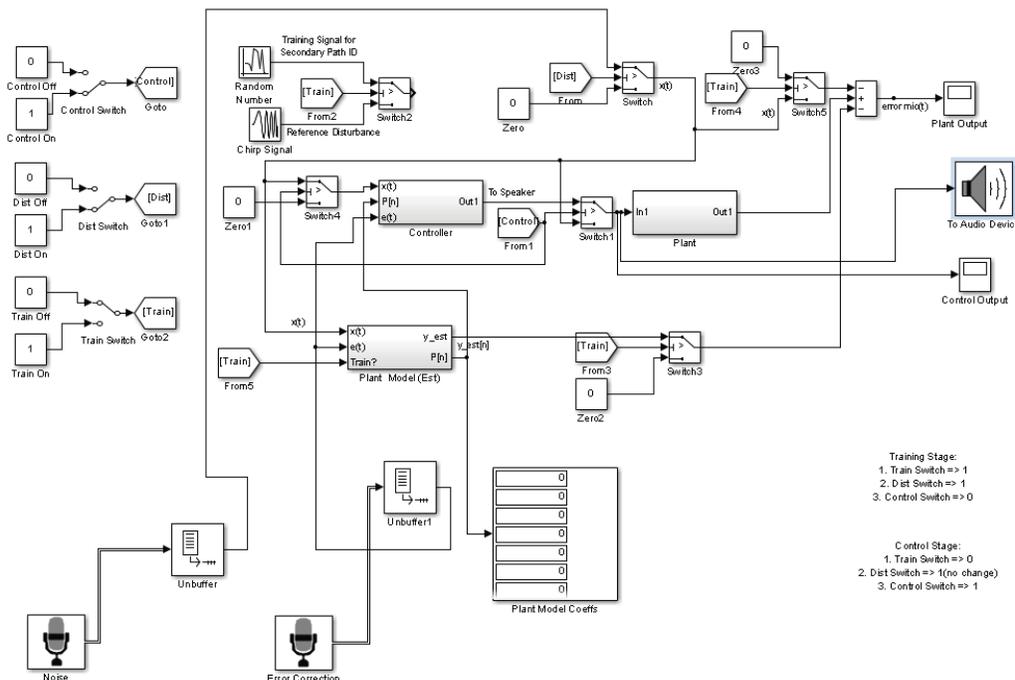
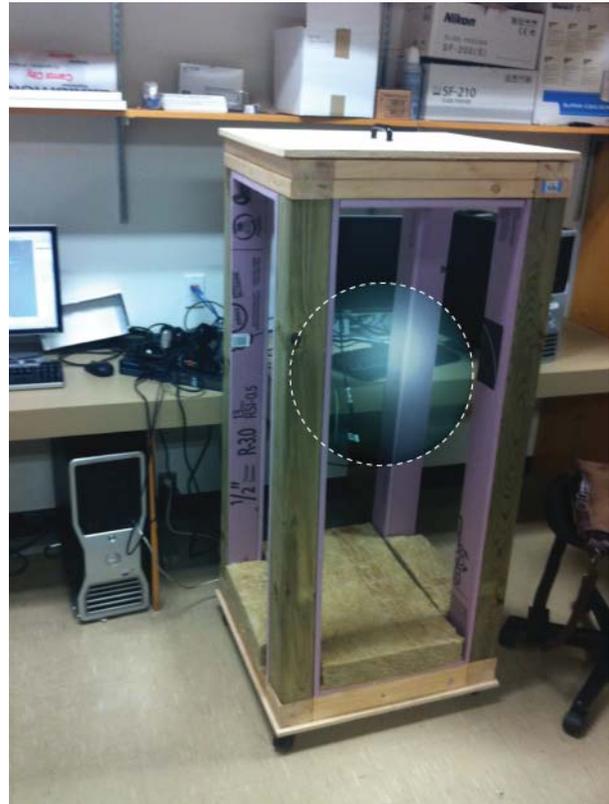
### APPENDIX A - ACTIVE NOISE CANCELLATION TEST



To test active noise cancellation in an open air setting, two 5" Mackie MR5 loudspeakers were set up facing each other. A phase flip algorithm was applied on one speaker. White noise was used to test the frequency attenuation. Both speakers produced the white noise signal except on speaker was propagating an anti-phase, hence, cancelling out the lower frequencies of the white noise.

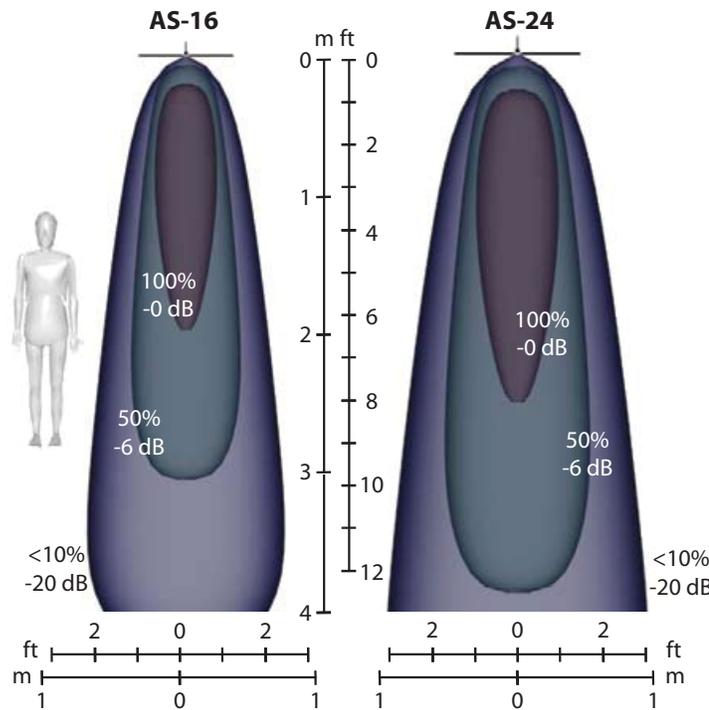
## APPENDIX B - ACTIVE NOISE CANCELLATION TEST WITH PARAMETRIC ARRAY LOUDSPEAKRS

A main experiment was set up to test the proposed active noise cancellation system facilitated by parametric array loudspeakers to achieve a zone of silence for tonal sounds. The system used MOTU Traveller DSP as the sound card for the input and output signals. Audiospotlight AS-16 parametric array loudspeaker was used as the control source. For control signal processing FXLMS algorithm coded by Agustinus Oey for MatLab was used to run the Simulink DSP model. Though the DSP was successful in simulation, due to batch processing method relaying the control signal, there was a 5 sec delay in the processing of the control signal. Further tests using a faster processor can alleviate this limitation.



Simulink model for VSE based on Agustinus Oey's MatLab FXLMS algorithm .

## Sound Field Distribution



Sound field distribution is shown with equal-loudness contours for a standard 1 kHz tone. The center area is loudest at 100% amplitude, while the sound level just outside the illustrated beam area is less than 10%.

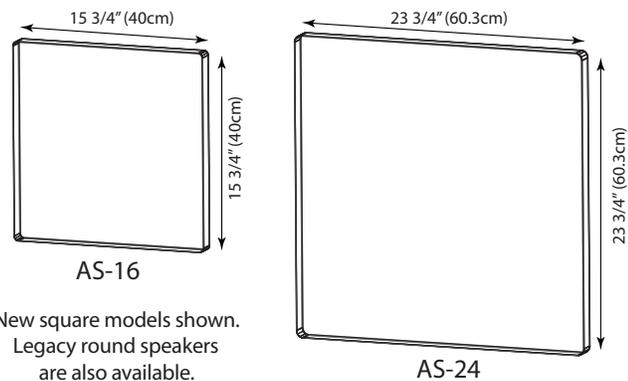
Audio Spotlight systems are much less sensitive to listener distance than traditional loudspeakers, but maximum performance is attained at roughly 1-2m (3-6 ft) from the listener.

Typical levels are 80 dB SPL at 1kHz for AS-16, and 85 dB SPL for AS-24 models. The larger AS-24 can output about twice the power and has twice low-frequency range of the AS-16.

## Amplifier Specifications

Input: RCA line-level audio  
 Power draw: 65W max (AS-24)  
 25W max (AS-16)  
 Output: BNC coax cable  
 (25' / 7m included)  
 Controls: Volume, tone, on/off  
 Voltage: 100-240V 50/60Hz  
 Dimensions: 6" w x 7" d x 1.6" h  
 (15cm x 18cm x 4cm)

## Speaker Dimensions (thickness ~0.5" / 1 cm)



Holosonic Research Labs, Inc.  
[www.holosonics.com](http://www.holosonics.com)  
 617-923-4000 info@holosonics.com

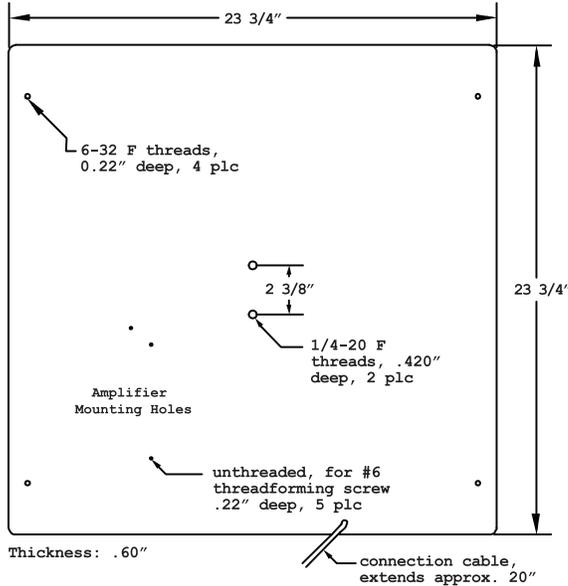
Add **sound...**  
 and preserve the **quiet.**<sup>™</sup>

# audio **spotlight**®

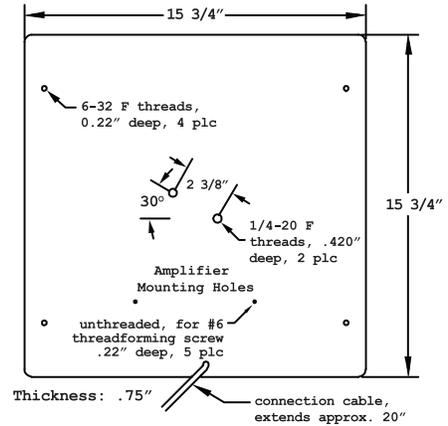
directional sound system

## Speaker and Amp Dimensions

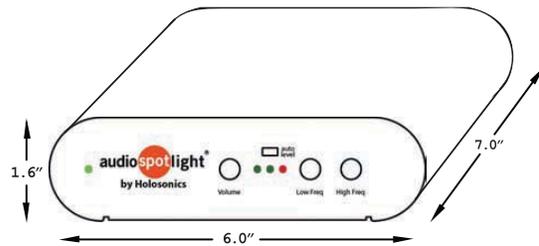
**AS-24 - Rear Dimensions**



**AS-16 - Rear Dimensions**



### Amplifier Dimensions



### Dimensions and Weights

#### AS-16 Speaker

Dimensions: 15.75" x 15.75" x 0.75"  
40 cm x 40 cm x 1.9 cm

Weight: 5.5 lbs (2.5 kg)

#### AS-24 Speaker

Dimensions: 23.75" x 23.75" x 0.60"  
60.3 cm x 60.3 cm x 1.5 cm

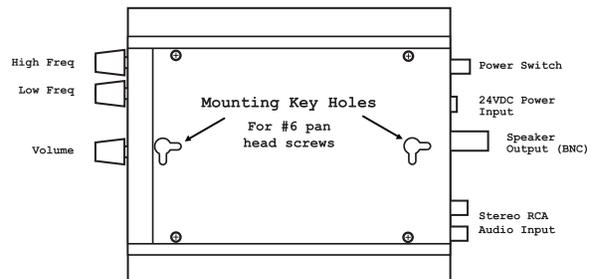
Weight: 12.5 lbs (6 kg)

#### Amplifier

Dimensions: 6.0" x 7.0" x 1.6"  
15 cm x 18 cm x 4.0 cm

Weight: 2.25 lbs (1 kg)

### Amplifier - Bottom Panel



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Add **sound**...  
and preserve the **quiet**.™



```

T=1000;

% We do not know P(z) and S(z) in reality. So we have to make dummy paths
Pw=[0.01 0.25 0.5 1 0.5 0.25 0.01];
Sw=Pw*0.25;

% Remember that the first task is to estimate S(z). So, we can generate a
% white noise signal,
x_iden=randn(1,T);

% send it to the actuator, and measure it at the sensor position,
y_iden=filter(Sw, 1, x_iden);

% Then, start the identification process
Shx=zeros(1,16); % the state of Sh(z)
Shw=zeros(1,16); % the weight of Sh(z)
e_iden=zeros(1,T); % data buffer for the identification error

% and apply least mean square algorithm
mu=0.1; % learning rate
for k=1:T, % discrete time k
    Shx=[x_iden(k) Shx(1:15)]; % update the state
    Shy=sum(Shx.*Shw); % calculate output of Sh(z)
    e_iden(k)=y_iden(k)-Shy; % calculate error
    Shw=Shw+mu*e_iden(k)*Shx; % adjust the weight
end

% Lets check the result
subplot(2,1,1)
plot([1:T], e_iden)
ylabel('Amplitude');
xlabel('Discrete time k');
legend('Identification error');
subplot(2,1,2)
stem(Sw)
hold on
stem(Shw, 'r*')
ylabel('Amplitude');
xlabel('Numbering of filter tap');
legend('Coefficients of S(z)', 'Coefficients of Sh(z)')

% The second task is the active control itself. Again, we need to simulate
% the actual condition. In practice, it should be an iterative process of
% 'measure', 'control', and 'adjust'; sample by sample. Now, let's generate
% the noise:
X=randn(1,T);

% and measure the arriving noise at the sensor position,
Yd=filter(Pw, 1, X);

```

```

% Initiate the system,
Cx=zeros(1,16);      % the state of C(z)
Cw=zeros(1,16);      % the weight of C(z)
Sx=zeros(size(Sw));  % the dummy state for the secondary path
e_cont=zeros(1,T);   % data buffer for the control error
Xhx=zeros(1,16);     % the state of the filtered x(k)

% and apply the FxLMS algorithm
mu=0.1;              % learning rate
for k=1:T,           % discrete time k
    Cx=[X(k) Cx(1:15)]; % update the controller state
    Cy=sum(Cx.*Cw);    % calculate the controller output
    Sx=[Cy Sx(1:length(Sx)-1)]; % propagate to secondary path
    e_cont(k)=Yd(k)-sum(Sx.*Sw); % measure the residue
    Shx=[X(k) Shx(1:15)]; % update the state of Sh(z)
    Xhx=[sum(Shx.*Shw) Xhx(1:15)]; % calculate the filtered x(k)
    Cw=Cw+mu*e_cont(k)*Xhx; % adjust the controller weight
end

% Report the result
figure
subplot(2,1,1)
plot([1:T], e_cont)
ylabel('Amplitude');
xlabel('Discrete time k');
legend('Noise residue')
subplot(2,1,2)
plot([1:T], Yd)
hold on
plot([1:T], Yd-e_cont, 'r:')
ylabel('Amplitude');
xlabel('Discrete time k');
legend('Noise signal', 'Control signal')

```

# APPENDIX C - VARYING FREQUENCIES



Frequency of male voice.



Frequency of city traffic.



Frequency of a crowd of people in a mall