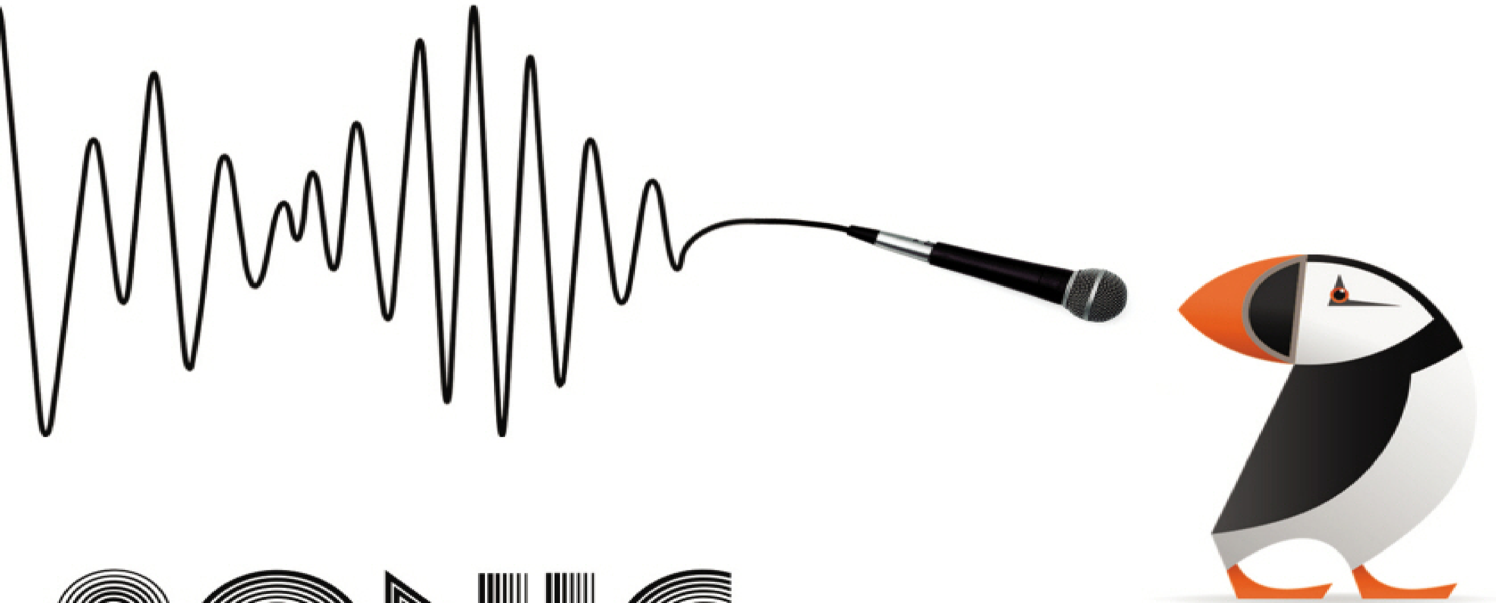

SONIC WONDERLAND

A SCIENTIFIC ODYSSEY OF SOUND

TREVOR COX

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About the Book

As an acoustic engineer, Cox has spent his career eradicating odd noises – echoes in concert halls, clamour in classrooms. But then he heard something so astonishing that he had an epiphany: rather than quashing curious and bizarre sounds, we should be celebrating them – the ‘sonic wonders of the world’.

Sonic Wonderland is the story of his investigation into the mysteries of these sonic wonders. Cox travels to the Mojave Desert where sand dunes sing. In France he discovers an echo that tells jokes. In California he drives down a musical road that plays the William Tell Overture.

Touching on physics, music, archaeology, neuroscience, biology, and design, Cox explains how sound is made and altered by the environment, how our body reacts to peculiar noises, and how these mysterious wonders illuminate sound’s surprising dynamics in everyday settings – from your bedroom to the opera house.

Sonic Wonderland encourages us to become better listeners in a world dominated by the visual and to open our ears to the glorious cacophony all around us.

About the Author

Trevor Cox is Professor of Acoustic Engineering at the University of Salford and President of the Institute of Acoustics. He has presented numerous science radio documentaries and has written for the *New Scientist*. He is an associate editor for an international journal of acoustics. Twitter: @trevor_cox

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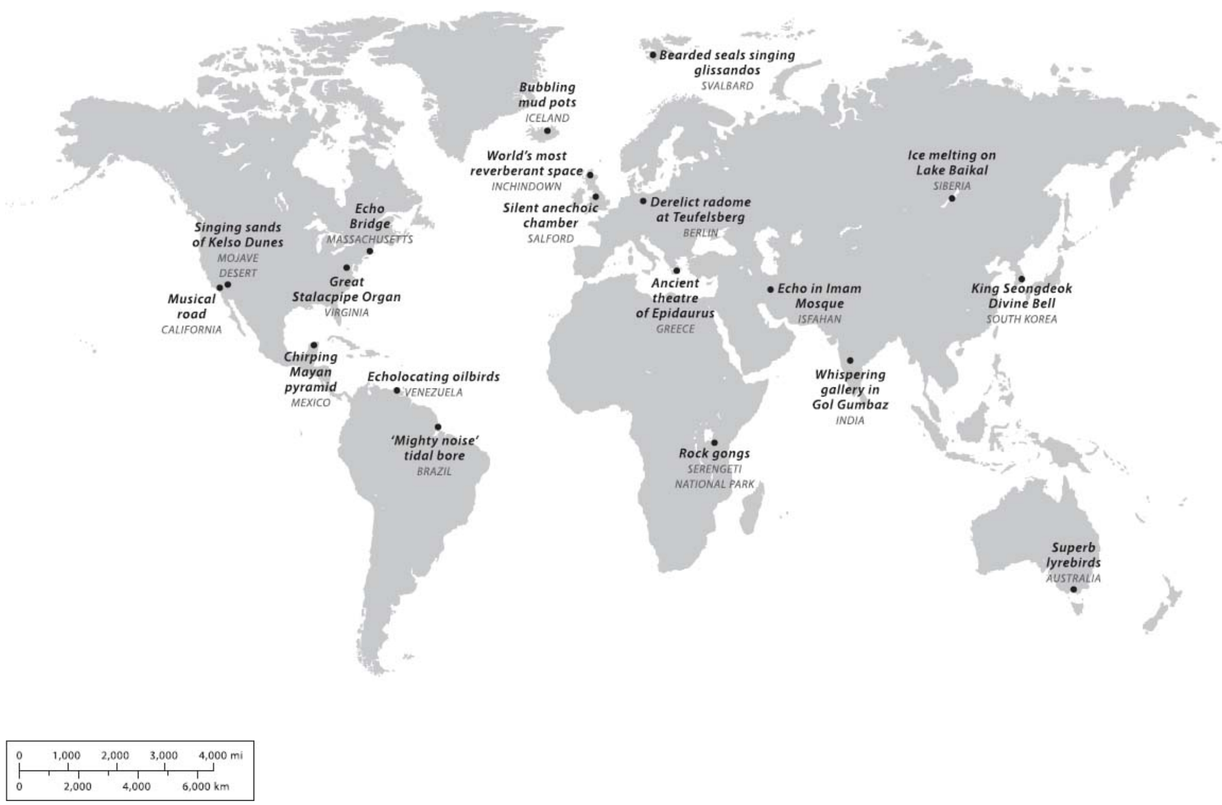
Unless otherwise stated, images are drawn by Trevor and Nathan Cox. Richard Deane took the Aeolus Photograph (figure 4.1). The satellite image of clouds showing airflow around Alejandro Selkirk Island (figure 8.7) is © NASA Goddard Photo and Video photo stream.

THE SONIC WONDERS OF THE WORLD



Visit www.sonicwonderland.co.uk to listen to some of the sonic wonders of the world.

To Deborah

Sonic Wonderland

A Scientific Odyssey of Sound

Trevor Cox

THE BODLEY HEAD
LONDON

Prologue

‘Is it safe?’ A noxious odour was invading my nostrils as I stared down the open manhole. The metal ladder disappeared into the darkness. I had assumed a radio interview on the acoustics of sewers would involve an official and authorised visit. Instead, it started with a walk into a London park on a summer’s evening. Bruno, the interviewer, produced a large key from his backpack, opened up a convenient manhole cover, and invited me to climb down. Was it legal to wander around the sewers without permission? What if the tunnel suddenly flooded? What about a canary to warn of poisonous gases? Meanwhile, strolling commuters ignored us as we gazed into the gloom.

I repressed my anxieties and climbed gingerly down the ladder to the sewer about 6 metres below. This was a storm drain built in Victorian times, a long cylindrical tunnel lined with bricks. The floor was treacherous and slippery, and the smell made my skin crawl. I clapped my hands as best I could with rubber gloves on and started to count in my head very slowly – ‘one, two, three . . .’ – timing how long it took the sound to die away. After 9 seconds a distant rumbling echo returned to me. Sound travels a kilometre every 3 seconds, so my clap had travelled a round trip of 3 kilometres. Later on, far away down the tunnel, we discovered the staircase off which the sound had bounced; it was draped in disgusting debris.

I found it difficult to avoid head-butting the stalactites hanging from the low ceiling. Sadly, these were not brittle rock, but crusty, fatty deposits clinging to the bricks. These foul stalactites broke off, worked their way down the back of my shirt and scraped my skin. Since I'm tall, my head was very close to the ceiling – the worst place for the revolting stalactites, but the optimal position for observing an unexpected acoustic effect. As the radio interview started, I noticed my voice hugging the walls of the cylindrical tunnel and spiralling into the distance. Speech spun around the inside of the curved sewer like a motorcyclist performing in a Wall of Death. While every other sense was being overwhelmed with revulsion, my ears were savouring a wonderful sonic gem. This impressive spiralling toyed with me as I tried to work out what was causing the effect. It was so different from anything I had experienced before that I started to doubt what I was hearing. Was it just an illusion, with the sight of the cylindrical sewer fooling my brain into thinking the sound was curving? No; when I closed my eyes, the reverberance still embraced my voice and twisted it around the tunnel. What was causing the sound to stay at the edges of the sewer and not cross into the middle? I have worked in architectural acoustics for twenty-five years, yet the sewer contained a sound effect I had not heard before. I also noticed that Bruno's voice was embellished with a metallic twang as it echoed in the sewer. How was that possible in a place devoid of metal? We were surrounded by bricks.

During those hours listening to the sewer, I had an acoustic epiphany. My particular expertise is interior acoustics – that is, the way sound works in a room. Most of my work has focused on discovering ways to mask or minimise unwanted sounds and acoustic effects. Not long after completing my doctorate, I pioneered new ways of shaping room surfaces that now improve the sound in theatres and recording studios around the world. Above the stage of the Kresge Auditorium at the Massachusetts Institute of Technology, you can see the gently undulating reflectors I designed to help musicians hear each other. For a rehearsal hall at the Benslow Music Trust in Hitchin, Hertfordshire, I designed corrugations to adorn a concave wall in order to stop sound reflections from all being focused onto a single point in the room and thereby altering the timbre of the musical instruments.

In recent years I have been researching how poor acoustics and high noise levels in classrooms affect learning. It seems obvious that pupils need to be able to hear the teacher and have a certain amount of quiet to learn, yet there are architects who have designed schools that are acoustic disasters. My bête noire is open-plan schools, where doors and walls are dispensed with, resulting in the noise from one class disturbing others because there is nothing to impede the sound. The Business Academy Bexley in London opened in 2002 and was short-listed for the prestigious Royal Institute of British Architects' Stirling Prize. The open-plan design caused so many noise problems, however, that the school and local education authority had to spend £600,000 installing glass partitions.[1] Part of my research into schools involved playing noise at pupils as they tried to complete simple tasks involving reading comprehension or mental arithmetic. In one test, playing the babble of a noisy classroom at a cohort of fourteen- to sixteen-year-olds lowered their cognitive abilities to those of a control group of eleven- to thirteen-year-olds who were working in quieter conditions.

I am currently working with colleagues to improve the quality of user-generated content online. I started the project after getting frustrated listening to distorted and noisy soundtracks on Internet videos. We are developing software that will automatically detect when an audio recording is poor – for instance, checking whether there is wind noise whistling past a microphone. The idea is to alert users to poor sound conditions before they start recording, or to use audio processing to weed out some of the interference, just as a digital camera looks for flaws and automatically adjusts exposure time and focus. But before we can write the software, we are grappling with people's perceptions of audio quality. When you record your child playing in a school concert, how much does the quality of the recording matter? My personal feeling is that audio distortions can be much more important than visual ones. A blurry video with a clear recording of a loved one singing captures that special moment much better than a clear video in which the lyrics are unintelligible and the voice distorted.

But as I splashed about in the sewer, I realised that distortions can sometimes be wonderful. Despite having studied sound intensely for decades, I had been missing something. I had been so busy trying to remove unwanted noise that I had forgotten to listen to the sounds themselves. In the right place a 'defect' such as a sound focus, or the metallic, spiralling echo in the sewer, could be fascinating to listen to. Perhaps ugly, strange and distorted sounds could teach us something about how acoustics work in everyday situations or even how our brain processes sound. By the time I emerged out of the sewer through a manhole in a leafy suburban street, I decided I wanted to find more such unusual acoustic effects. And not just the ugly ones. I wanted to experience the most surprising, unexpected and sublime sounds – the sonic wonders of the world.

Somewhere on the vast Internet I imagined I would be able to find a list of other strange sounds to experience. But after a lengthy shower scrubbing away the odorous memory of the sewer, and a few hours online, I realised it would not be so easy. The dominance of the visual has in fact dulled all of our other senses, especially our hearing. Our obsession with sight has led us to produce loads of images of bizarre and beautiful places, but surprisingly few recordings of wonderful sounds. Like the Soundkeeper in Norton Juster's classic children's book *The Phantom Tollbooth*, I sense among my fellow citizens a lack of appreciation of subtle sounds and an increase in discordant noises.[2] But rather than lock away sounds and enforce silence as the Soundkeeper does, I wanted to seek out, experience and celebrate wonderful aural effects. What fascinating sounds are out there if we just 'open' our ears? While there are many books on unwanted noise and how to abate it, there are not many on how to listen better – something acoustic ecologists call *ear cleaning*.

> Open [a] book now and gently open the pages and just listen to the sound . . . that's a very complex sound . . . first there is the sound of the thumb or finger as it brushes against the edge of the paper before you turn the page and then there is the sound of the page as it turns.[3]

This is Murray Schafer, the grandfather of acoustic ecology, demonstrating how even a simple object, such as the book in your hands, can make many different sounds. It is 'full of possibilities', he writes. This quote from an ear-cleaning exercise comes from a Canadian radio programme from the 1970s. No cotton swabs are involved, however; listeners improve their hearing skills by changing how their brains process sound, not by physically cleaning their ears.

Schafer tells his listeners to remove all distractions – 'like eating, drinking or smoking: well, smoke if you have to but don't let it distract you' – to control your breathing and close your eyes to 'amputate the visual sense'. The experience could be disconcerting, because although the radio script is reminiscent of a meditation CD, the bossy narration is far from soothing. The recording reminds me of a scene from an old black-and-white espionage film in which a villain is trying to brainwash the hero.

Despite the unnerving tone, the programme includes some intriguing exercises: invent an onomatopoeic name for the sound of a hardback book being slammed shut (*thump* or *thud* does not quite work), or predict and then imitate the sound of a piece of paper being scrunched up and thrown against a wall. Nowadays you might have to choose something different to play with – an e-book reader being dropped in the bath?

Schafer is evangelical about ear cleaning, believing that children should do it to improve their sonic sensibilities, and that people who shape our sound world, such as urban planners, should undergo the process regularly. In his seminal book *The Soundscape*, Schafer suggests some other ear-cleaning activities you could try. The technique he uses most often is to get people to declare a moratorium on speaking for a day, while eavesdropping on sounds made by others. He wrote, 'It is a challenging and even frightening exercise,' and successful participants 'speak of it afterward as a special event in their lives'.[4] But my colleague and fellow acoustic engineer Bill Davies believes this is taking it too far: 'If you want to give people an acoustic epiphany,' he told me, 'then a short journey on a soundwalk is a better way of going about it.'[5]

A soundwalk can be a simple activity. All one has to do is stroll for a couple of hours without saying a word, focusing intently on the sounds of the city or countryside. I first did this with an eclectic group of thirty engineers, artists and acoustic ecologists. We formed a slow-moving strung-out crocodile weaving through the streets of London. The cacophony of cars, planes and other people starkly contrasted with our own enforced silence. I felt like an extra in an old B movie, part of a procession of possessed humans being summoned by some alien force – silent zombies walking toward impending doom.

This particular group was recreating a soundwalk that Murray Schafer and colleagues had first carried out in the 1970s. We followed a set of prescribed exercises – from trying to count the number of propeller aircraft heard flying over the formal gardens in Regent's Park (pointless nowadays, though you can still count jets), to trying to suppress a loud noise by consciously ignoring it. I chose the loudest sound around, a pneumatic drill that was hammering away on Euston Road.

Ignoring a pneumatic drill proved very hard to do; indeed, at first it seemed impossible. Trying to disregard the pounding noise immediately made it more obvious because of the way our hearing works. Seals might be able to close their outer ears when diving, but humans have no way of physically shutting out sound. We have no ‘earlids’, and there is no auditory equivalent of closing our eyes or averting our gaze. Our hearing is constantly picking up sounds. We cannot physically stop the eardrum, the tiny bones in the middle ear, or the tiny hair cells in the inner ear from vibrating. Inevitably, the inner ear generates electrical signals, which travel up the auditory nerve into the brain. Fingernails scraping down a blackboard or the climax to a Beethoven symphony, good sounds or bad – the ear sends the audio upwards. The brain then has to work out which sounds are important and must be paid attention to, and which ones can be safely ignored. Something noisy and abrupt, like the roar of a tiger or the squealing of car brakes, catches our attention immediately so that we can fight or take flight. When we hear something less threatening, we have to think and decide which sound we want to attend to.

Auditory attention was first researched after the Second World War, as the military tried to understand why fighter pilots sometimes ignored crucially important audible messages.[6] A typical experiment had people listening on headphones and saying aloud the words they heard through one of their earphones. Simultaneously, researchers played a distracting message in the other ear. After this test, subjects could recall very little about the distracting message. Scientists would make changes to the distracting speech – switching talkers or language, and even playing the sound backwards – yet most people failed to spot the changes.[7] Although many of us believe we listen to multiple sounds simultaneously, and even believe that women are better than men at such multitasking, these tests demonstrate that such an ability is an illusion. We listen to one thing at a time and rapidly change our attention from one sound to another.

Consequently, back on Euston Road the only way to quieten the pneumatic drill was to focus very hard on another sound. I used two strangers having a boisterous conversation outside a pub. Trying to actively suppress the drill just made it louder, but switching my attention elsewhere meant I could exploit the brain's amazing cognitive ability to suppress background noise.

During the hours focusing on the soundscape around me, I heard the fleeting melody of birdsong, an unexpected hush in the piazza outside the British Library, an auditory sense of enclosure as I entered the tunnel under Euston Road, and the subtle squelching of an underinflated bicycle tyre on a pavement. Interesting sounds suddenly became more obvious and audible. I was amazed to hear how different railway stations sounded; the throb of idling diesel trains in King's Cross made that station seem more authentic than St Pancras or Euston. Of course, it was not all positive; the clatter of cheap rolling suitcases being dragged along platforms and pavement proved intensely annoying.

Acoustic ecologists have amazing ears for such sonic subtleties, but soundwalking and ear cleaning can help anyone learn to consciously tune in to such previously overlooked delights. We have at our disposal immense cognitive power to analyse sound – after all, listening to and decoding music and speech is an incredibly complex task – yet it is something we take for granted. A soundwalk reveals that there are sounds in our everyday life that, if we choose to listen to them, will surprise us with their diversity and uniqueness. Even something as mundane as footsteps encompasses a huge range of sounds, from the clack-clack of high heels on marble, to the squeak of trainers on a gym floor. If we can unconsciously learn to recognise colleagues approaching unseen along a corridor from the rhythm of their walking, what else might we be able to accomplish with dedicated effort? Our ears play an immensely important role in how we perceive the world. In this book I hope to show how we can filter things differently, to move us away from our over-reliance on the visual, showing how diverting our attention in this way can enrich our enjoyment and understanding of the spaces we inhabit.

Acoustic ecologists are also concerned with aural conservation. Soundscapes do not need to be preserved in aspic, but we need to make sure that great sounds are not lost through neglect – not just calls from endangered species, but also other sounds that are important to us. Not long after my first soundwalk, I interviewed artists in Hong Kong for a BBC programme about endangered sounds. They lamented the loss of the bells in the tower at the Star Ferry pier in Kowloon in 2006, which used to play the Westminster Chimes. Redevelopment and well-meaning renovations can ruin precious acoustic effects, as happened about a century ago in the US Capitol in Washington, DC, when architects altered the dome and dulled the focusing that used to distort the speech of senators. Acoustic scientists and historians have only recently begun documenting, preserving and reconstructing the acoustics of a very few important places. Combining the latest methods for predicting architectural acoustics, three-dimensional sound reproduction and new archaeological research, scientists have begun to reveal some of the ancient sounds of Greek theatres and prehistoric stone circles.

Another major threat to the sonic landscape is the smog of transportation noise. Underwater, baleen whales have to sing louder to overcome shipping noise. In cities, birds such as great tits have changed their tunes to be heard above the traffic. Of course, humans suffer as well: nearly 40 per cent of Americans want to change their place of residence because of noise, 80 million EU citizens live in unacceptably noisy areas, and one in three UK citizens have been annoyed by neighbour noise.[8] Unintelligible announcements in train stations, restaurants where you have to shout to hold a conversation, and annoying mobile phone ringtones – we unnecessarily suffer a large number of acoustic deficiencies.

Some of these sound excesses are of our own making. Many of us take a large daily dose of music and speech through headphones that isolate us from the sounds of our environments. It has become part of our daily routine: compared with only five years ago, youngsters spend 47 more minutes a day listening to music and other audio.[9] We drive around in cars cocooned in our own portable and controllable soundscape. But then we miss out on simple sonic pleasures: not just the twitter of birds singing out defiantly against the roar of traffic, the laughter of schoolchildren in a playground, or a snippet of overheard gossip from strangers passing in the street, but the wonderful and unique acoustics of the places we wander through each day. City districts can be visually ugly, but even there, a dingy corner covered in graffiti can harbour the most extraordinary zinging sound effects.

For decades, acoustic engineers have been trying to reduce unwanted noise, but many attempts have been defeated by changes in society. A modern car is much quieter than an old clunker, but increased traffic means the average city noise level has remained about the same. As the rush hour extends and motorists seek out quieter roads, peaceful places and times are disappearing. What should we do about this noise? I believe that telling people to stop doing noisy things is futile. It is better to encourage listening and curiosity. Although technology often produces unwanted noise, new devices are also creating bizarre and wonderful sounds every day. Gadgets emit distinctive pings and buzzes that people will cherish and be nostalgic about. The chime of the pinball machine takes me back to hanging out with friends in my youth. My children will likely have fond memories of the iPhone click, long after the device has been supplanted by more sophisticated technologies. With better awareness of the sonic wonders, I hope people will demand better everyday soundscapes.

Since the trip into the sewer, my hunt for sonic wonders has morphed into a full-blown quest. I set up an interactive website (Sonic Wonders.org) to catalogue my discoveries and serve as a forum for people to suggest enticing sounds for further investigation. After a talk at a conference in London, a delegate told me about a large, spherical room called the Mapparium at the Mary Baker Eddy Library in Boston, where even non-ventriloquists can throw their voice. This illusion plays with the mental processing that allows us to locate sound sources, processes that evolved to protect us from predators creeping up on us from behind. A conversation during a TEDx event in Salford made me want to find out more about the moths that have evolved decoy tails to fool echolocating bats. Rummaging through old proceedings from academic conferences has revealed a gold mine of acoustic curiosities, neglected phenomena that devoted scientists have studied alongside their day-to-day research.

Friends and colleagues, and even complete strangers, have given me examples of quirky acoustics and fascinating science. My research has uncovered the ways in which sounds have inspired musicians, artists and writers: how church acoustics had to be adapted when the liturgy moved from Latin to English, how writers portray subtle acoustic effects such as the indoor feeling at Stonehenge, and how sculptors have ingeniously made sonic crystals that reframe ambient noise.

As a scientist, I want to pick apart what is going on. I went on holiday to Iceland many years ago and marvelled at bubbling mud pools, but now I wonder, what caused them to gloop? I have seen Internet videos of a giant Richard Serra sculpture in which a hand clap resounds like a rifle shot. What is happening there? Why does throwing a rock onto a frozen reservoir produce the most astonishing high-pitched twangs? Some of these questions have no readily available answers, but in searching for explanations, I hope to gain insight into how our hearing works, both in these special places and in our everyday lives.

What makes a sound so extraordinary as to be considered one of the sonic wonders of the world? In my quest for these aural gems, I will rely in part on my gut reaction as a trained acoustic engineer: what might be surprising or weird enough to make the experts stop and wonder? One example might be the sonic behaviour in an old water cistern in Fort Worden, Washington, which one audio engineer described as ‘the most acoustically disorienting place I have ever visited’.[10] Or perhaps it will be something that takes us back in time to the experiences of our ancestors. Were the Mayan pyramids in Mexico deliberately designed to chirp? Was this sound used as part of their ceremonies? Sonic wonders might also be very rare acoustic effects: only a few sand dunes sing, droning like a propeller aircraft – a phenomenon that astonished both Charles Darwin and Marco Polo.

Travel guides will be useless. Like most of our texts, they privilege the visual, describing beautiful vistas and iconic architecture while ignoring sounds and unusual acoustics. I was delighted to find the whispering gallery in St Paul’s Cathedral featured in my London guidebook, but this is a rare exception. The whispering gallery appeals to me as a physicist because the movement of sound around the dome fools listeners into hearing mocking voices emerging from the walls.

Music will play an important role in the search, not least because it can provoke strong emotions. Listen to one of Mahler's grand symphonies in an auditorium like the Great Hall of the Viennese Music Association (Wiener Musikverein) in Vienna, and you might feel shivers down your spine. Music is a powerful research tool, used by psychologists and neuroscientists to tweak the emotions of humans to reveal the workings of the brain. Research into music has taught us a great deal about listening – why some things sound nasty or nice, and how evolution has shaped our hearing. Often the best scientific understanding of sound and how we perceive it comes from research into music. But music and speech engage us on a different level. Indeed, recognisable patterns in music and speech can *distract* us from acoustics and natural sounds. This book will thus go beyond music and oratory to discover sounds that are overlooked or neglected.

Inevitably, I will have to use words and analogies from the visual world to describe sonic phenomena; we have relied on the visual for too long for our language to have developed otherwise. A newspaper interview with the artist David Hockney once said something about *seeing* that has stuck with me:

> We don't just see with our eyes, [Hockney] argues, we use our minds and emotions as well. That is the difference between the image which the camera makes – a split-second record from a fixed viewpoint – and the experience of actually looking, of passing through a landscape, constantly scanning and switching our focus. That is the difference between the passive spectator and the active participant he wants us to become. The latter sees not just geometrically, but psychologically as well.[11]

I want to explore what would happen if we transpose these ideas from the visual to the aural. To see what fascinating sounds reveal themselves, and discover what effect they have on us. This book is about the psychology and neuroscience of hearing as observed and explored by a physicist and acoustic engineer. And no other place embodies the combination of these disciplines better than a concert hall. Strangely, we know more about the human response to classical music in an auditorium than about many more common sounds. Why not, then, start with the most important quality of a concert hall: reverberation?

1

The Most Reverberant Place in the World

G*UINNESS* RECOGNISES A few world-record sounds: the loudest purr of a domestic cat (67.7 decibels, in case you wondered), the loudest burp by a male (109.9 decibels), the loudest clap measured (113 decibels) – all very impressive. But as a scholar in architectural acoustics, I am more intrigued by the claim that the chapel of the Hamilton Mausoleum in Scotland has the longest echo of any building. According to the 1970 *Guinness Book of Records*, when the solid-bronze doors were slammed shut, it took 15 seconds for the sound to die away to silence.

Guinness describes this phenomenon as the 'longest echo', but this is not the right term. Experts in architectural acoustics, like me, use the term *echo* to describe cases in which there is a clearly distinguishable repetition of a sound, as might happen if you yodelled in the mountains. Acousticians use *reverberation* when there is a smooth dying away of sound.

Reverberation is the sound you might hear bouncing around a room after a word or musical note has stopped. Musicians and studio engineers talk about rooms as being *live* or *dead*. A live room is like your bathroom: it reflects your voice back to you and makes you want to sing. A dead room is like a plush hotel room: your voice gets absorbed by the soft furnishings, curtains and carpet, which dampen the sound. Whether a room sounds echoey or hushed is largely a perception of reverberation. A little bit of reverberation causes a sound to linger – a bloom that subtly reinforces words and notes. In very lively places, such as a cathedral, the reverberation seems to take on a life of its own, lasting long enough to be appreciated in detail. Reverberation enhances music and plays a crucial role in enriching the sound of an orchestra in a grand concert hall. In moderation, it can amplify the voice and make it easier for people to talk to each other across a room. Evidence suggests that the size of a room, sensed through reverberation and other audio cues, affects our emotional response to neutral and nice sounds. We tend to perceive small rooms as being calmer, safer and more pleasant than large spaces.[1]

I got my chance to explore the record-holding mausoleum at an acoustics conference in Glasgow that included in its programme a trip to the chapel. Early on Sunday morning, I joined twenty other acoustic experts outside the gates of the mausoleum. Constructed from interlocking blocks of sandstone, it is a grand, Roman-style building rising 37 metres into the air and flanked by two huge stone lions. An uncharitable observer might try to infer something about the tenth Duke of Hamilton's manhood from the building's shape, which is a stumpy, dome-topped cylinder. It was built in the mid-nineteenth century, but all the remains have long since been removed. The building sank 6 metres because of subsidence caused by mines, which left the crypt vulnerable to flooding from the River Clyde.

The eight-sided chapel is on the first floor and is dimly lit by sunlight shining through the glass cupola. The chapel has four alcoves and a black, brown and white mosaic marble floor. The original bronze doors that start the world-record echo (modelled on the Ghiberti doors at the Baptistry of St John in Florence) are propped up in two of the alcoves. Opposite the new wooden doors is a plinth, built of solid black marble, that once supported an old alabaster sarcophagus of an Egyptian queen within which the embalmed duke was laid to rest. The sarcophagus was actually a bit small for the duke, and our guide delighted in relaying gruesome stories about how the body was shortened to get it to fit. On the day I was there, the plinth was covered in laptops, audio amplifiers and other paraphernalia for acoustic measurements.

The chapel was meant to be used for religious services, but the acoustics made worship impossible. It was like a large Gothic cathedral, and I found it difficult to talk to my acoustics colleagues unless they were close to me, since the sound bouncing around the chapel made speech muddy and indistinct. But was this the most reverberant place in the world? The record is important to me as an acoustic engineer because the study of reverberation marked the beginning of modern scientific methods being applied to architectural sound.

The scientific discipline of architectural acoustics began in the late nineteenth century with the work of Wallace Clement Sabine, a brilliant physicist who, according to the *Encyclopaedia Britannica*, 'never bothered to get his doctorate; his papers were modest in number but exceptional in content'.[2] Sabine was a young professor at Harvard University when, in 1895, he was asked to sort out the terrible acoustics of a lecture hall of the Fogg Museum, which (in his own words) 'had been found impractical and abandoned as unusable'.[3] The hall was a vast, semicircular room with a domed ceiling. Speech in the room was largely unintelligible – a muddy soup of sound more characteristic of the Hamilton Mausoleum than of a well-designed lecture hall. The most forthright critic of the space was Charles Eliot Norton, a senior lecturer in fine arts.

Imagine Norton standing at the front of this vast hall trying to expound on the arts – formally dressed and sporting a large moustache, sideburns and receding hair. His students would first get the sound travelling directly from the professor to their ears – the sound that goes in a straight line by the shortest route. This direct sound would then be closely followed by reflections – the sound bouncing off the walls, domed ceiling, desks and other hard surfaces in the room.

These reflections dictate the *architectural acoustics* – that is, how people perceive the sound in a room. Engineers manipulate acoustics by changing the size, shape and layout of a room. This is why acousticians like me have an uncontrollable desire to clap our hands and hear the pattern of reflections. (My wife was appalled when I clapped my hands in a crypt of a French cathedral. This must go down as one of the more esoteric ways of embarrassing your spouse.) After clapping my hands, I listen for how long it takes the reflections to become inaudible. If sound takes a long time to die away – if it reverberates for too long – then speech will be unintelligible as consecutive words intermingle and become indecipherable. As Henry Matthews wrote in a nineteenth-century text on sound, reverberation 'does not politely wait until the speaker is done; but the moment he begins and before he has finished a word, she mocks him as with ten thousand tongues'.[4] This is what happened whenever Norton tried to lecture. Students might quip that most lectures are incomprehensible even before the speech is mangled by the room, but Norton was a good communicator and a popular teacher. In this instance it was indeed the fault of the room and not the performer.

Large spaces with hard surfaces, such as cathedrals, the Hamilton Mausoleum or the cavernous lecture hall at the Fogg Museum, have reflections that persist and are audible for a long time. Soft furnishings absorb sound, reducing reflections and speeding the decay of sound to silence. Wallace Sabine's experiments involved playing around with the amount of soft, absorbing material in the lecture hall – a method that makes him seem like an overenthusiastic fan of scatter cushions. Sabine took 550 one-metre-long seat cushions from a nearby theatre and gradually brought them into the lecture hall in the Fogg Museum to observe what would happen. He needed quiet, so he worked overnight after the students had gone home and the streetcars had stopped running, timing how long it took sound to die away to nothing. He did not use clapping, maybe because it is difficult to clap consistently unless you are a professional flamenco musician, but instead used a note created by an organ pipe.

Sabine called the time it took for the sound to wither to silence the *reverberation time*, and his work established one of the most important formulations in acoustics. The equation shows how the reverberation time is determined by the size of the room, which is measured by its physical volume, and the amount of acoustic absorbent like the seat cushions from Sabine's experiments or the wall covering of 2.5-centimetre-thick felt that he ultimately used to treat the acoustics of the lecture hall. One of the crucial decisions engineers make when designing a good-sounding room – whether a grand auditorium, a courtroom or an open-plan office – is how long the reverberation time should be. Then they can use Sabine's equation to work out how much soft, absorbing stuff is needed.[5]

Alongside reverberation time, a designer has to consider frequency, which directly relates to perceived pitch. When a violinist bows her instrument, the string behaves like a tiny skipping rope, whipping around in circles. If she plays the note that musicians call *middle C*, the skipping rope turns a full circle 262 times every second. The vibration of the violin radiates 262 sound waves into the air every second, which is a frequency of 262 hertz (often abbreviated to Hz). The unit was named after Heinrich Hertz, the nineteenth-century German physicist who was the first to broadcast and receive radio waves. The lowest frequency a human can hear is typically around 20 hertz, and for a young adult the highest is about 20,000 hertz. However, the most important frequencies are not at the extremes of hearing. A grand piano has notes from only about 30 to 4,000 hertz. Outside that range we cannot easily discern pitch, and all notes start to sound the same. Beyond 4,000 hertz, melodies are turned into the mindless whistling of someone who is tone-deaf. The middle frequencies where musical notes reside are also where our ears are most efficient at amplifying and hearing sounds. Most speech falls into this range as well, which is why in rooms where music will be played, acoustic engineers concentrate on designing for a frequency range of 100 to 5,000 hertz.

In 2005, Brian Katz and Ewart Wetherill used computer models to explore the effectiveness of Sabine's treatment in the Fogg Museum. They programmed the size and shape of the lecture hall into a computer and employed equations that describe how sound moves around a room and reflects from surfaces and objects. They then added virtual materials to the walls and ceiling of their simulated lecture hall to mimic Sabine's felt treatments. Although the absorbers improved the acoustics, the intelligibility of speech was still poor in places. As one student reported, there were seats where hearing was easy, and conversely, 'there were dead spots where hearing was often extremely difficult'.[6] Though the treatments were imperfect, Sabine's experiments opened the door for a wide variety of acoustic exploration. His equations remain the foundation of architectural acoustics to this day.

I love walking into a concert hall and hearing the contrast between the small entrance corridor and the huge expansive space of the auditorium. From the claustrophobic passageway, one enters a palpably vast room, passively perceiving the quiet chatter of anticipation amongst the audience and the occasional loud sound stirring the mighty reverberation. Entering Symphony Hall in Boston is particularly exciting for me. Symphony Hall is Mecca for many acousticians, for it was in this very hall that Wallace Sabine applied his newfound science to create an auditorium still considered to be one of the top three places to hear classical music in the world. Completed in 1900, it has a shoebox shape – long, tall and narrow – with sixteen replica Greek and Roman statues set into the walls above the balconies. On my visit I settled into one of the creaky black leather seats while the Boston Symphony Orchestra was tuning up on the raised stage in front of the gilded organ. As the first piece began, I could immediately understand why audiences and critics wax lyrical about the place. The hall beautifully embellishes the music, having a reverberation time of about 1.9 seconds.[7] When the orchestra stopped playing at the end of a moderately loud phrase, it took nearly 2 seconds for the sound to become inaudible.

At an outdoor concert, an orchestra might play from a tented stage while the audience enjoys a picnic. The night often ends with bottles of champagne and fireworks exploding overhead. These concerts are fun, but the orchestra sounds thin and remote. In contrast, within a great venue like Symphony Hall the music appears to fill the room and envelop the audience from all sides. The reverberation inside amplifies the orchestra, allowing for more impressive loud playing. It also makes sounds linger a little, enabling musicians to make smoother transitions from note to note. Reverberation helps create a more blended and rich tone. As the twentieth-century conductor Sir Adrian Boult put it, ‘The ideal concert hall is obviously that into which you make a not very pleasant sound and the audience receives something that is quite beautiful.’[8]

The transformational effect of reverberation is not restricted to classical music; it is also used extensively in pop. The 1947 number one hit ‘Peg o’ My Heart’ (a slow instrumental played on giant harmonicas), by Jerry Murad’s