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Introduction

ON JUNE 20, those attending the Neue Musik (New Music) Berlin 1930 festival hosted by the Berlin Academy of Music listened to the debut of a new electric musical instrument: the trautonium.[1] The trautonium was named after its inventor, electrical engineer and physicist Friedrich Adolf Trautwein, who was assisted by Oskar Sala, a student of the renowned avant-garde composer Paul Hindemith at the academy. The performance featured a trio of trautoniums played by Sala, Hindemith, and Rudolf Schmidt. The reviews were mixed. Some felt the instrument was a laboratory joke, while others thought it was astonishing—the sensation of the festival—and that the concert marked the start of a new age of electroacoustic instruments. The numerous responses to the trautonium throughout its lifetime map nicely onto the myriad views concerning modernity. Those who embraced the instrument's so-called futuristic sounds saw it as reflecting a brave, new world, while others who did not share the optimism of such a future sharply criticized the instrument and insisted it neither was, nor ever would be, the music of the future. This book tells the story of that instrument.

The trautonium has enjoyed a lifespan of nearly a century, although its popularity has considerably waned.[2] It has gone through a number of instantiations, including the *Volkstrautonium* (people's trautonium), *Rundfunktrautonium* (radio trautonium), *Konzerttrautonium* (concert trautonium), and *Mixturtrautonium* (mixture trautonium). The instrument has been featured in a variety of entertainment genres, including classical music; *Gebrauchsmusik* (light music intended for amateurs); *Rundfunkmusik* (radio music, or music specifically composed for the radio); theater music; and sound effects for films and commercials. It has appeared in ballets, radio dramas, and operas, including several of Richard Wagner's—and at Bayreuth, no less. A number of leading composers—Paul Hindemith, Werner Egk, Paul Dessau, and Carl Orff—either wrote pieces for the instrument or used it as a substitute for other instruments. Renowned film director Fritz Lang used the trautonium in *The Indian Tomb*, which he directed in 1959. The trautonium's finest hour came in 1963, when

FIGURE 0.1. The first three musicians on the trautonium who performed at the Neue Musik Berlin 1930 festival hosted by the Berlin Academy of Music, June 20. Friedrich Trautwein is standing, Oskar Sala is seated on the left, Rudolf Schmidt in the middle, and Paul Hindemith on the right. *Source:* Kestenberg, *Kunst und Technik,* facing 112.

Alfred Hitchcock had Sala play the instrument to produce the sounds of birds screeching and flapping their wings in his classic horror film *The Birds*. I like to say that the trautonium is the most famous instrument you have never heard of but that you have most likely heard.

In the first part of the book, I trace the confluence of a number of scientific, technological, political, and musical communities that existed during the 1920s and '30s and that resulted in the invention of the instrument. One such community is centered around early German radio, whose origins date back to the first public broadcast on October 29, 1923, in Berlin. The same equipment, skills, and practices used in radio were also employed in building the trautonium; indeed, the origin of the trautonium is imbricated with the early history of radio. While I agree with scholar Paul Théberge that the digital age witnessed the destruction of the boundary between media and instruments, I argue that that dismantling was already occurring in early-twentieth-century Germany.[3]

The second community that was necessary for the trautonium's invention comprised physicists and electrical engineers working on electroacoustics. This newly formed community—as leading German acoustician and physicist Erwin Meyer insisted—was created to solve the problems then faced by fledgling radio. Early German radio broadcasts were plagued by acoustical distortions that hampered the broadcast, making it difficult for even the most discerning musical ears to differentiate between instruments or voices. Physicists and electrical engineers, with the assistance of physiologists and phoneticians, were charged with fixing these distortions, particularly the ones that affected frequencies at the upper and lower ends of the radio station's frequency range, or bandwidth. The engineers and physicists of the Weimar Republic transformed radio into an instrument for relaying music and the human voice. This would become important for propaganda purposes after the Nazis' rise to power in January 1933.

The third intellectual community that contributed to the invention of the trautonium was musicians, particularly those experimenting in the relatively new genre of electric music. Numerous composers of the 1920s and '30s—including Hindemith, Edgard Varèse, Olivier Messiaen, Joseph Schillinger, and Carlos Chávez, to name just a few—were fascinated by these new instruments. Some musicians, such as Max Butting, Kurt Weill, Ernst Toch, and Hindemith, composed works that were specifically suited for the new medium of radio. A number of musicians were also engineers. For example, electrical engineer and organist Jörg Mager, author of *Eine neue Epoche der Musik durch Radio* (*A New Epoch of Music by means of Radio*), invented the spherophone in 1926.[4] Most famously, around 1920, Russian-Soviet electrical engineer and cellist Lev Sergeyevich Termen—better known in the West as Leon Theremin—invented the theremin, of which he conceived while repairing his radio. The theremin was very popular in Germany.

The site where these various communities—electroacoustics, radio research, and electric music—came together was also the laboratory where the trautonium was invented: the Funkversuchsstelle, which opened on May 3, 1928, in the attic of the Berlin Academy of Music. Later, the laboratory would be known as the Rundfunkversuchsstelle (the Radio Experimental Laboratory, or the RVS). Funded predominantly by the Prussian Ministry of Culture and the Reich's Broadcasting Corporation (the Reichs-Rundfunk-Gesellschaft), the RVS hosted immensely fruitful collaborations between natural scientists, radio engineers, and musicians who would go on to improve radio broadcast fidelity, develop *Rundfunkmusik,* teach the use of radio equipment to music students, and eventually invent an electric musical instrument. The RVS was the crucible where the skills, theories, and practices of these scholars were forged.

Given my own passions and abilities, I shall approach this book as a historian of science and technology, albeit one with musical training and an interest in musicology. I have spent much time (perhaps too much) thinking about German history, specifically the various Germanies of the past century and their corresponding (and often antithetical) political views of modernity. Those three related areas of interest—history of science and technology; musicology; and the histories of the Weimar Republic, the Third Reich, and the Federal Republic of Germany—provide the foundation of this book.

What are this book's intended contributions? For natural scientists, engineers, and historians of science and technology, this study offers the history of the physics and electrical engineering upon which radio was predicated. It details the role of those disciplines in inventing a cadre of electric musical instruments after World War I. This is also a story about a scientific instrument, namely the harmonic analyzer, the history of which was hitherto largely unknown despite its importance to the history of electroacoustics and radio. By following the development of late-nineteenth- and early-twentieth-century disciplines, such as applied physics, physiology, phonetics, psychology, radio and electrical engineering, and electroacoustics, we begin to see the various ways in which scholars in those fields defined and understood important musical and scientific phenomena such as tone color (also known by its French term, timbre), fidelity, and the formation of speech sounds.

While much more famous as a musical instrument, the trautonium became a scientific instrument used to adjudicate between Hermann von Helmholtz's theory of resonance and Ludimar Hermann's subsequent theory of impulse (or shock) excitation to explain the creation of vowel sounds and the development of a musical instrument's tone color. Trautwein was convinced that the trautonium was the electrical counterpart to the human voice organs and certainly saw his instrument as settling the debate on the side of L. Hermann. Finally, the book details the status of natural scientists and engineers in the various Germanies. Many famously were blamed for Germany's defeat in World War I, felt alienated throughout the Weimar Republic, tried their best to ingratiate themselves with governmental officials by actively supporting the Nazis, and attempted once again to regain acceptance after the defeat of the Nazis, despite their active roles in World War II.

Since radio provided challenging intellectual and practical problems beyond the limited horizons of traditional physics and electrical engineering, it is important that I address the technical aspects of physics and electrical engineering. Omitting the technical knowledge would render the story woefully incomplete. I ask for the reader's patience as I guide them through the denser material. We need to appreciate and comprehend the labor and skill (both intellectual and manual) that these scholars brought to the problem. Two works in particular are relevant here: Wittje's important work on the history of electroacoustics and Yeang's outstanding tome detailing the technical history of the transformation of noise from an annoyance that electrical engineers attempted to ameliorate in electric sound reproduction to a subject relevant to understanding statistical detection, prediction, and the transmission of information.[5]

I hope the book will also appeal to musicologists. The trautonium was the quintessential modernist musical instrument, producing a new type of music that wished to distance itself both from classical compositions as well as those of Arnold Schoenberg, Alban Berg, and Anton Webern. This work also provides us with a better understanding of early radio and the music broadcast by important station managers such as Hans Flesch of Frankfurt, and later Berlin, by shedding light on the early years of Rundfunkmusik and its composers. It also contributes to the history of tone color during the 1920s and '30s, a period that witnessed an important metamorphosis in its meaning. By telling a hitherto unknown story of electric music and its relationship to electroacoustic and electronic music, musicologists can also begin to see the historically contingent processes of negotiation that defined those terms. The trautonium illuminates the relatively unknown debates between Trautwein and Sala on the one hand, and the pioneers of the Cologne Studio for Electronic Music—particularly Werner Meyer Eppler—on the other, as detailed in their correspondence. Their letters raise interesting questions about the definition of electronic music: Which aesthetic should be included and which should be excluded? What is the role of the composer in relation to the performer? Is there such a thing as an "authentic composition"?

Another relevant aspect of this book to musicologists interested in the twentieth century is the attempt to situate the trautonium within the longue durée of proto-synthesizers, as it shared a number of important features with them, including the synthesis of music and vowel sounds as well as the ability to imitate a large range of timbres and sounds. While many scholars realize that electric music predates World War II, we hear relatively little about instruments that shared some of the attributes of the synthesizers of the 1950s and '60s. RCA's Mark II (designed by Harry Olson and Herbert Belar), Max Mathews's work at Bell Labs on digital-computer music, and the Moog synthesizer were all postwar inventions.[6] When Mathews spoke on the history of synthesizers in 1985, he insisted that their origins were in the early 1950s with the work of Vladimir Ussachevsky and Otto Luening in New York City, Pierre Schaeffer in Paris, and Karlheinz Stockhausen in Cologne.[7] Oskar Sala wished to differentiate between his mixture trautonium and synthesizers for both entrepreneurial reasons and reasons of musical performance.[8] Unlike more modern synthesizers, the mixture trautonium did not possess sound envelopes or voltage-controlled filters or amplifiers. The functions of those devices were achieved by manually controlled circuits. As we shall see, Sala wished to produce many of the effects created by synthesizers himself.[9] In his view, the machine should never completely replace the human.

Finally, for German historians and those interested in German studies, this book discusses the interest of leading German intellectuals of the 1920s and '30s in German radio in general and the RVS in particular, including Bertolt Brecht, Kurt Weill, Walter Benjamin, Alfred Döblin, and Theodor Adorno. The trautonium's history during the Third Reich was an intriguing one. While one might think that the Nazis would consider electric music degenerate, the opposite was true. The trautonium could serve their purposes in creating an aesthetic of "steely Romanticism," contribute to *Hausmusik* for the *Volk*, and provide entertainment for mass gatherings. It can therefore shed light on the complicated relationships the Nazis had with music and technology. Claiming that they opposed everything "modern" is simply fallacious. This work also offers an account of the trautonium's contribution to industry and cultural films as well as television and cinema commercials—and music culture in general—in the Federal Republic of Germany.

The instrument is quite unique, even among the electric musical instruments of the period. Its sounds were produced by a glow-discharge (neon) tube and later thyratrons, rather than using frequency beats as was the case with the theremin and ondes Martenot, or tuned tube oscillators as was the case with the Coupleux-Givelet organ and the Hammond Novachord. The laboratory where the instrument was invented, the RVS, was also unique. Due to the lab being housed in a musical academy as opposed to an engineering company, the majority of its work was dedicated to music. The RVS was, in a sense, a mirror image of Bell Telephone Laboratories: engineers and scientists in this US laboratory focused their research on the transmission of speech, and music initially played a secondary role. The historian can use the RVS as a foil to the Bell Telephone Laboratories, which were created by AT&T and Western Electric. Finally, no other country possessed the caliber of such intellectuals in those numbers writing about early radio and its laboratories. All of these points begin to explain the distinctiveness of the trautonium and the context of its invention. While this book does not seek to support the German *Sonderweg*, it does describe a number of peculiar aspects of German music, science and engineering, and politics that go a long way to explain why the trautonium was an invention of the Weimar Republic.[10]

Musical aesthetics is one theme that runs through this work. Addressing the disciplines with which this book wishes to engage—history of science and technology, musicology, and German history—I investigate how scientists and engineers defined and measured musical aesthetics, how musicians defined and experienced those aesthetics, and how politicians shaped or quelled them. One example of musical aesthetics is tone color, defined as the quality of a sound that is unique to the instrument or voice that created it. That is to say, it explains the difference in tone between a cello playing a note at 220 Hz with a particular volume, and a piano playing that note with the identical pitch and volume. Timbre ties together the trautonium, electroacoustics, politics, and music. The instrument could imitate the tone colors of a number of traditional musical instruments as heard by the ears of skilled musicians and as seen by oscillograms it produced when compared with the oscillograms generated by those traditional instruments. Timbre also was relevant to the radio, since it was difficult to broadcast with sufficient fidelity: distortions in the broadcast's tone color were due in large part to the radio transmission and receiving equipment, namely microphones, loudspeakers, and amplifiers. A history of musical aesthetics of the 1920s and '30s is simultaneously a history of those radio parts; therefore, musical aesthetics were inextricably linked to electroacoustic theories, skills, and practices. Since radio created an important market for these devices, engineers and physicists busied themselves with rendering the requisite improvements, thereby improving broadcast, much to the appreciation of attentive audiences.

Emily Dolan has provided us with a wonderful account of timbre, from its origins with the works of Jean-Jacques Rousseau to its solidification in the nineteenth century.[11] She argues that Joseph Haydn's style of orchestration of the late eighteenth century must be understood through the emergence of the public's interest in various instruments' timbres. More recently, Dolan and Alex Rehding have coedited a collection of essays on timbre.[12] The volume illustrates how tone color has now become a key theme of research for historians (including historians of science and technology), musicologists, philosophers, science-and-technology-studies scholars, and sound-study scholars.

A history of tone color is also a history of fidelity, another example of musical aesthetics that ties the book together. A vast majority of physicists and engineers had initially defined fidelity of timbre as a static comparison of the oscillograms generated by harmonic analyzers depicting the relative amplitudes of the overtones of broadcast voices and instruments with those of the original sounds.[13] During this period, however, an ever-increasing number of physicists and engineers—including Trautwein—as well as physiologists and psychologists realized that timbre was not static and that it hung over the interval of playing a note: what we now call the sound envelope. The initial portion of playing a note (the attack) possesses different timbres than the decay, which in turn possesses different timbres from those of the release. Only by recapturing and consistently reproducing the entire process could one begin to speak of fidelity of tone color. In addition, engineers at Bell Telephone Laboratories began to show that tone color was also somewhat dependent on volume.

Finally, psychologists increasingly criticized what they claimed were wrong-headed attempts by many physicists and electrical engineers to understand timbre without acknowledging the role of human perception.

Jonathan Sterne's pathbreaking work, *The Audible Past*, has provided us with the definitive study on fidelity, arguing that the creation of music is just as constructed as its reproduction.[14] Emily Thompson's *The Soundscape of Modernity* offers us a compelling aural, cultural, and technological history of twentieth-century America.[15] She demonstrates how the Edison Company persuaded the American public that a reproduction in the form of a phonograph could be a worthy substitute for a live performance. Reproducing fidelitous sound was the goal of those who had stakes in radio's success. Musicians, natural scientists, and radio engineers all actively participated in rendering radio a legitimate medium.

Given the range of expertise and disciplines of those interested in sound fidelity, perhaps it should not come as a surprise that one should actually speak of fidelities, rather than fidelity, during this period. The various definitions, however, had one thing in common: they were based on the problems that plagued early radio broadcasts. For Adorno, a fidelitous reproduction was one in which the listener's experience of a radio broadcast of a Beethoven symphony mirrored their experience in a concert hall. Even by the early 1940s, he famously argued that such a reproduction was not possible. Another definition dealt with the listener's inability to differentiate between the upper pitches of the flute and violin and hear the lower notes of the double bass. Engineers, natural scientists, and musicians also spoke of how the volumes of various groups of instruments during a broadcast differed from the relative volumes in the performance hall. In addition, researchers began to realize that the human ear does not hear linearly, but logarithmically, meaning that we hear some portions of the audio spectrum better than others. For example, one needs to greatly intensify the energy supplied to a pitch sounding at 100 Hz in order to hear it at the same volume of a pitch at 1000 Hz. Finally, we sometimes hear a third tone, known as combination tone, when two pitches with different frequencies are sounding together. Some of these tones are a product of the human ear: they cannot be detected by a physical apparatus such as a harmonic analyzer. They are referred to as subjective tones. The subjective could never be fully removed from the "objectively" generated results of scientific instruments. Properties of the human ear and mind needed to be better understood. Interesting debates arose in laboratories when skilled musicians insisted that they heard something that their state-of-the-art equipment did not register.

Timbre reproduction was only one problem, albeit a crucial one, of several problems with broadcast fidelity. The definitions of fidelity as the relative intensities of the overtones of the original sound and those of its reproduction were critical to many of my historical actors. In addition, this interest in timbre fidelity over the radio led directly to the invention of the trautonium and is therefore emphasized in this book.

Given the various aspects of fidelity, I shall stress when my actors are speaking, or when it is my voice you hear. Michel Chion makes a relevant and important point: if there is more than one historical definition of fidelity, it is impossible to argue that fidelity is something objectively improved by tinkering with microphones, loudspeakers, and amplifiers.[16] As a historian, I am more interested in how my historical actors defined fidelity as it related to the broadcast timbres, and whether they thought it could be objectively quantified, and if so how.

The term *Naturtreue* (or "faithful to nature") was often used during the 1920s and '30s by musicians, physiologists, physicists, and engineers to indicate how close the broadcast sound was to the original. The word also referred to artworks depicting natural scenes as well as physiological and anatomical representations. *Klangtreue* (or "faithful to sound")—the word used most often today to refer to musical fidelity—was also used during the 1920s and '30s, albeit far less than Naturtreue.[17] Of course, *Treue* was also used.[18] As we shall see, however, the sounds created by voices and musical instruments in the broadcast studio were just as contrived and orchestrated as the corresponding transmitted sounds.[19]

Another definition of fidelity addressed in the second portion of the book is one not based on sound reproduction, but on the faithfulness to a cause or belief. Such was the case with Sala's opportunism and Trautwein's dedication to fascism, as the trautonium was transformed during the Third Reich into an "instrument of wonder." Of course, such fidelity needed to be effaced after the war, and Sala was much more successful than Trautwein in distancing himself from Nazism. Despite the trautonium's ability to imitate the tone colors of numerous traditional instruments with an impressive degree of fidelity (according to my historical actors), because of its versatility, it was also simultaneously infidelitous, as it could shed its affiliation both with any particular tone color and the prevailing political ideology during which it was invented and improved. By considering the themes of tone color and fidelity from a number of disciplines, it becomes clear that the agreements and disagreements between various professions add to our understanding of the historically contingent notions of subjectivity, objectivity, and the roles of the human and machine in defining musical aesthetics.

Like the Moog synthesizer, the trautonium contributed to a plethora of aesthetic qualities, which change over time. The first one was the aesthetic of *Neue Sachlichkeit* (New Objectivity), which was one of machine-like precision, order, and experimentation. Neil Grosch has argued that Neue

Sachlichkeit was an attempt to fuse modern music with society. It included *Gebrauchsmusik*, which by design was aimed at popular audiences, an attempt to distance itself from "highbrow" virtuosic music, Rundfunkmusik, and *Zeitoper*, the latter being a Weimar Republic invention with socially and politically relevant themes. Zeitoper often employed modern technology with a view to reach a much larger audience than had previously been the case.[20] Two other aesthetic qualities of the trautonium addressed in the book are imitation and the creation of unique, futuristic sounds and timbres.[21] Should newly invented electric musical instruments imitate traditional acoustical ones with a view to replicate or even replace them, or should they generate their own unique sounds? The original trautonium could do both, as Trautwein and Sala insisted from the moment of its invention. (Sala, after initially assisting Trautwein, went on to construct later models of the instrument on his own.) These two critical properties—imitation and creativity—appealed to numerous diverse audiences over a span of over seven decades. In an interesting way, they reflected the complexities of Berlin, a city that simultaneously wished to embrace modernity and was horrified by it. Some Berliners applauded the futuristic sounds the instrument could create, while others saw it as an important contribution to traditional German music. During the early 1930s, imitation was lauded by the radio company Telefunken as a marketing ploy for the Volkstrautonium, a household version of the instrument, since it was important to German Hausmusik. Imitation was also a favored characteristic among certain Nazi circles, particularly when it involved house music for the Volk. The Nazi Party did, however, sponsor trautonium concerts that played arrangements of classical pieces with new, unique tone colors and new works specifically composed for the trautonium. In addition, a key aesthetic during the Third Reich was "steely Romanticism," a phrase coined by the Reich Minister of Public Enlightenment and Propaganda, Joseph Goebbels. The trautonium, a Germanic invention after all, was seen as cultivating that particular aesthetic quality.

After the war, the trautonium was often described as generating a new, modern, even futuristic, aesthetic, as technology increasingly shaped artistic expression. The trautonium's ability to do so was an important ingredient in an aesthetic that wished to distance itself from the horrors of the Third Reich. The novel sounds now emanating from the instrument were an attempt to extricate itself from its fascist past. Ironically and critically, the trautonium could contribute both to the fascist aesthetic of imitation and "steely Romanticism" as well as an aesthetic of novelty meant to completely undermine Nazi aesthetics. Such versatility (some might say instability), however, was simultaneously a disadvantage, since any instrument possessing many timbres lacks a unique timbre of its own. After the war, Sala's gumption ensured the instrument's success. By stressing that the instrument was not restricted to one type of aesthetic, he reached out to his listeners to assist him in creating new niches. It was the perfect strategy in the land of the *Wirtschaftswunder*, or economic miracle, of West Germany during the 1950s and '60s.

While imitation and creativity are epistemologically contradictory, the proponents of both the trautonium and the new medium of radio often shifted between claims of naturalism based on imitation and fidelity, and the invention of new sounds and genres. They are, in essence, two sides of the same coin. As with other (later) electronic musical instruments, the trautonium's interface elements were a trade-off between the player in the moment of performing and the complexity of tone shaping. Similarly, there was a continued shuttling between attempting to render the radio broadcast as true as possible to the original performance (mimesis) and arguing for a new type of music composed for the radio (invention).[22] Engineers and listeners were constantly on the lookout for proxies of truth-to-nature or imitation.[23] At the same time, the trautonium and the radio were meant to provide new and unique forms of experience for their performers and audience. One thinks of the electric guitar. Invented during the early 1930s, it initially was meant to increase the volume produced by acoustical guitars rather than offer a new type of sound. Jazz guitar performers used electric guitars to play typical guitar solos in large bands; extra volume was therefore necessary. As time went on, the electric guitar became an instrument that could create new timbres and sounds and contributed to numerous musical genres.

In addition to musical aesthetics, the politics of the various German nation-states and their numerous views on modernity are also themes that run throughout the book. As we have seen, politics is intricately and inextricably linked to musical aesthetics. The nation-state also shaped the research and roles of engineers and scientists in society. State politics played a role from the start of my story, as radio came under the purview of the Reich's Ministry of the Post Office. In addition, the RVS was predominantly state funded.

The year 1923, which witnessed the birth of German public radio, was a particularly tumultuous one for Germans. The terms of the Treaty of Versailles ending World War I were devastating. Political turmoil was a common occurrence throughout the Reich. Deadly skirmishes between the Communists and Nazis, which had formed as a political party in 1920, became a daily routine in cities such as Berlin. In January, French and Belgian troops occupied the Ruhr region of western Germany in response to Germany's refusal to pay war reparations. In August, German Chancellor Gustav Stresemann's first Cabinet was sworn in, which was followed closely by the swearing in of his second Cabinet about seven weeks later. In October a separatist government formed in the Rhineland Palatinate. In addition, both communists and fascists attempted to overthrow the Republic in different states. On November 23, Stresemann resigned, having only served for just over a hundred days. Political chaos spelt economic doom: on November 15, the value of a German paper mark plummeted to approximately 1 trillion Marks per US dollar. Pictures of Germans carrying wheelbarrows containing suitcases full of Reichsmarks to purchase food at a local market became iconic.

Weimar German radio was dedicated to being impartial (*Überparteilichkeit*, or literally being "above partisanship") and was also committed to underscoring the various dialects and cultures found throughout the Reich. No one language (such as *Hochdeutsch*), nor one culture among the German Volk was considered to stand above the rest. A "centralized decentralization," as it was referred to, was the necessary model for Weimar radio's success. Shortly before the rise of fascism, however, that had changed. German radio began to take political sides and infamously was used as an instrument of propaganda by Goebbels from 1933 until the end of the war. Under the Nazis, it was meant to unify the German Volk by stressing Hochdeutsch and various cultural characteristics shared by all Germans. The *Volksempfänger*, or radio receiver, was often referred to in the vernacular as "Goebbelsschnauze," or "Goebbels's snout," and was now cheap enough for the workers to afford.

Just because the pioneers of early Weimar radio wished it to be impartial, it would a mistake to see it as being free from politics. As a result of the explosion of radio's popularity throughout Europe and the United States in the late 1920s, various governments needed to impose restrictions on bandwidths to avoid unwanted interference due to the increase in the number of stations. These restrictions resulted in the cutoff of the overtones of high pitches and begin to explain why—in addition to the inefficiencies of the components of the transmitter and receiver—the soprano's voice did not come across as well in broadcasts as it did in live performances. Political and economic decisions that sacrificed the soprano's voice were made by men. Such a move was neither inevitable nor natural: there were alternatives.

The German nation-state also shaped engineering and scientific disciplines during the early twentieth century. The corresponding professions underwent rapid change from the late nineteenth century until well after World War II. By tracing the various discourses on modernity, particularly those espoused by leading engineers, one can begin to piece together their relationship with the German state and culture. By the second half of the nineteenth century, engineers were gaining in prestige, yet they still lagged behind those who were classically trained, the so-called *Bildungsbürgertum*, or the educated upper-middle class, whose education was based on the classical languages of Greek and Latin. The Bildungsbürgertum comprised the so-called free professions: high-ranking civil servants such as university professors, military officers, and church officials. A key to their education was German idealism as explicated in the works of Immanuel Kant, Johann Gottlieb Fichte, Johann von Goethe, and Friedrich Schiller. In contrast, engineers were trained in the so-called illiberal disciplines, which were taught at technical universities (*technische Hochschulen*) across the land. Members of the Bildungsbürgertum often viewed engineers, even those with advanced degrees, with disdain.

Given the importance of engineers to the rapid industrialization of the burgeoning nation, Kaiser Wilhelm II gave technical universities in 1899 the ability to grant the degrees of *Diplomingenieur* and *Doktoringenieur*. Not surprisingly, engineers with Doktoringenieur degrees wished to be treated as equals to those who possessed the equivalent of a PhD in the humanities. They, too, sought the coveted status of *Kulturträger*.[24] Trautwein, who received his Dr. Ing. from the Technical University of Karlsruhe in 1921, certainly felt he earned such a status. Technology was for him, as well as many other well-educated engineers of the period, an integral part of German culture. With the disastrous end of World War I, German scientists and engineers alike suffered from a crisis of identity throughout the Weimar Republic and were often viewed as being culpable for Germany's defeat. As Adelheid Voskuhl has pointed out, while engineers desperately sought to be members of bourgeois culture (*Bürgerlichkeit*), being influenced by right-wing, antimodern ideologies, they often simultaneously loathed its liberal attitudes and values. Industrialization, seen by many as one of the defining characteristics of liberal modernity, according to Voskuhl, was in reality the cause of its death.[25] Like a disproportionately high percentage of engineers, Trautwein joined the Nazi Party in 1933. Many of the educated elite were sympathetic to the Nazis' vision of a new and glorious future. A staunch supporter of Nazi ideology, Trautwein assisted the Nazi Party with his acoustical expertise on amplification for large, outdoor rallies. After World War II, Trautwein attempted to reestablish the role of educated engineers as Kulturträger by waxing poetic on both the philosophy of technology and the importance of technology to culture.

The Nazis' Reichsmusikkammer (Reich Chamber of Music), the musical state agency under the control of the Ministry of Public Enlightenment and Propaganda, subsidized a later version of the trautonium, the concert trautonium, built by Sala, who toured with the instrument throughout the Third Reich, in occupied territories such as Holland, France, and Hungary, and in allied countries, such as Italy, with support both of the Reichsmusikkammer and the *Kraft-durch-Freude* (Strength-Through-Joy) programs.

Various nation-states certainly played a role in the type of musical aesthetic that was acceptable after the defeat of the Nazis. Sala and, to a lesser extent, Trautwein did their best to cultivate the interest of the Allied powers in the trautonium after the end of the war. Sala actively sought out patronage from the Radio in the American Sector (RIAS) in Berlin. He also attempted to interest musicians in the Soviet sector of Berlin to build quartet trautoniums in the late 1940s. He subsequently found his niche in the capitalist industries of the Federal Republic of Germany.

This history of the trautonium is in part a story about the material culture of objects. As a material object of modernity, the trautonium challenges our preconceived notions about the isolation of various aspects of culture and science of the twentieth century. By offering a history of the trautonium, I hope to show how a musical instrument reconstituted the relationships between science, technology, politics, and musical aesthetics, thereby forcing us to rethink the notion of modernity.

The materiality of musical instruments, which owes much to Trevor Pinch and Frank Trocco's *Analog Days*—a pioneering work on the history of the Moog synthesizer—has become the subject of numerous investigations over the past two decades.[26] Emily Dolan and John Tresch's important work on organology traces the intersecting and divergent histories of music and science by looking at scientific and musical instruments. Musical instruments render the inner emotions and thoughts of a composer accessible to the outside world, while scientific instruments transport the external world into the thoughts of the inner world of a scientist's mind.[27] Similarly, the musicologist Rebecca Wolf has worked on the materiality of musical instruments, while the musicologist Alexander Rehding has written on the relationship between instruments and music theory.[28] Furthermore, Thomas Patteson's work has given us wonderfully contextualized accounts of several electric musical instruments, including the trautonium, during the 1920s, '30s, and '40s.[29]

The past twenty years have also witnessed the publication of many works linking the history of music with the history of science and technology. I seek to continue that trend by merging a history of music, specifically aesthetics, with the history of science and technology.[30] For example, Peter Pesic has written the longue durée history of the relationship between music and science, *Music and the Making of Modern Science*, and his more recent work, *Sounding Bodies*, elucidates the influence of both music and sound on the structure and content of biomedical sciences.[31] Historian of science Alexandra Hui demonstrates how leading physicists, physiologists, and psychologists dedicated themselves to understanding sound from a psychophysical perspective. She deftly argues how musical aesthetics were inextricably linked with the natural sciences.[32] Hui, Julia Kursell, and my coedited volume, *Music, Sound, and the Laboratory from 1750 to 1980*, proffer an account of how laboratory sciences changed the notion of sound over two hundred years. Newly invented laboratory techniques of sound detection and representation and the use of electricity and computers to generate sounds fundamentally altered acoustics as well as musical practice. The musicologist Kursell has written a number of important essays on nineteenth-century German science and music.[33] Theater and media studies scholar Viktoria Tkaczyk has recently shown how the elucidation of the function of the auditory cortex in the late nineteenth century influenced numerous academic disciplines in the natural sciences and humanities.[34]

While historians contributing to sound studies have argued for quite some time against separating aesthetics from science and technology, the theme is still unrepresented in the history of science and technology more broadly speaking. This work seeks to illustrate how one accounts for the mutual implications of aesthetics, science, and engineering. There have been a small number of important contributions on aesthetics and science provided by historians of science. Michael Dettelbach's influential essay is one of the first on this topic: he demonstrates how the Humboldtian aesthetic was based on precision measurement. I have offered examples along those lines with respect to physics and music. My *Harmonious Triads* explores how physicists such as Wilhelm Eduard Weber contributed to musical aesthetics in the nineteenth century. For example, Weber's work on compensated reed pipes, which were used to experimentally test the ratio of the increase in pressure and the increase in density of a sound wave, also led to the invention of organ pipes that could increase in volume without increasing in pitch. Organs now became expressive. Robert Brain's *The Pulse of Modernism* is an important study linking the origins of artistic modernism to physiological theories of perception forged in late-nineteenth-century French laboratories. "Physiological aesthetics" altered the way artists, poets, and musicians plied their craft and in so doing changed the notion of art itself. Deborah Coen interweaves a wonderful account of the relationship between science, politics, and aesthetic qualities in the visual arts and liberalism in nineteenth-century Vienna by tracing the history of the Erxleben family in her *Vienna in the Age of Uncertainty*.[35] John Tresch's *The Romantic Machine* is a magisterial tome addressing how the sciences and the arts, rather than being antithetical, were critical for uniting a deeply fractured nineteenth-century French society. Finally, Norton Wise argues for the importance of the aesthetic sensibilities involved in drawing and the visual arts to Hermann von Helmholtz's early work on physiology.

The trautonium itself has attracted the attention of scholars lately. Two recent works are doctoral dissertations in musicology and media studies: Benedikt Brilmayer, "Das Trautonium: Prozesse des Technologietransfers im Musikinstrumentenbau," and Christina Dörfling, *Der Schwingkreis: Schaltungsgeschichten an den Rändern von Musik und Medien*.[36] In a third, Peter Donhauser adroitly details the complex technological developments of the various instantiations of the trautonium from its origin to the mixture trautonium some twenty-two years later.[37] There has been, however, very little written on the instrument in English.[38]

Much like Aldous Huxley's *Brave New World*, where the protagonist Bernhard Marx does not appear until after the initial chapters, the protagonist of my story, the trautonium, does not immediately appear in my work either. Switching the roles just for the analogy, just as Marx disappears in favor of John in Huxley's work, the radio succumbs to the trautonium. I feel the trautonium's late appearance is justified, since I need to trace the various traditions that formed the instrument's context to appreciate how the instrument came about.

Chapter 1 details how early German radio was considered to be an experiment by one of its pioneers, Hans Bredow. Radio would teach and entertain the German people at a time of economic devastation and extreme political uncertainty in the aftermath of World War I. Brecht stressed that radio needed to be experimental in order to render transparent the arcane processes occurring daily in the Reichstag. He hoped the RVS would improve radio broadcasts, as he saw the apparatus as critical to the education of the German people. Radio created a new musical genre (Rundfunkmusik) and a spoken genre (*Hörspiele*, or radio dramas), which were invented because of the medium's popularity. Furthermore, new musical forms featuring electric musical instruments, such as the trautonium, were broadcast over the radio.

Chapter 2 traces the history of fidelity by investigating the challenges that physicists and engineers faced trying to improve the broadcasting of tone colors. Violins were often mistaken for flutes or clarinets. During opera broadcasts, the soprano's voice came across as dull. Such infidelity gravely threatened the young medium's future; therefore, it is not a surprise that there was a certain urgency in the research conducted on linear and nonlinear distortions that plagued broadcasts, as discussed in chapter 3. Throughout the 1920s and '30s, radio engineers and physicists used harmonic analyzers to study the effects of the components of the transmitter and receiver on the relative amplitudes of a sound's overtones. This provided scientists and engineers with a metric of fidelity that in turn could be used to determine the imperfections of the equipment that needed to be remedied. Scientists and engineers conducted their experiments in laboratories of major German electrical engineering companies such as Siemens & Halske, Allgemeine Elektricitäts-Gesellschaft (AEG), and Telefunken, collaborating with numerous governmental and university laboratories. Their major competitors were researchers at US companies, particularly Western Electric and American Telephone and Telegraph Company (AT&T), and Bell Telephone Laboratories (from 1925 onward), Radio Corporation of America (RCA), and General Electric (GE).

The RVS is the subject of chapter 4. Established in 1928, it was the site of experimentation of myriad issues for natural scientists, physiologists, phoneticians, engineers, and musicians. The RVS improved broadcast fidelity, invented a new instrument, and tested microphones, loudspeakers, and amplifiers. It contributed to the genre of Rundfunkmusik, taught students how to work with microphones, and it also hosted the experiments of Hindemith and his fellow Neue Sachlichkeit composer Ernst Toch on how changing the speed of a recorded sound alters the sound's timbre. Arnold Schoenberg stopped by the RVS and encouraged Trautwein and Sala to increase the range of the trautonium to the range of the grand piano. The musicologist, psychologist, and physiologist Carl Stumpf visited the RVS and was amazed by the number of overtones the trautonium could produce.

As discussed in chapter 5, the trautonium was invented during the height of Neue Sachlichkeit. Hindemith, one of the movement's leaders, was the first and by far the most important musician who composed pieces for the instrument. It was a period when electric musical instruments filled the ether waves of radio and concert halls. Debates erupted about this new genre of music. Was it an example of mechanical music? If not, how was it different? Could the new instruments be of assistance to what many felt was the stagnating genre of musical composition by unleashing new tone colors? Did musicians welcome or spurn the role played by natural scientists and radio engineers in establishing a new musical aesthetic?

Although the vocoder, invented in 1938 by Homer Dudley at Bell Telephone Laboratories, was much better at synthesizing speech, the trautonium predates it in synthesizing vowel sounds. The trautonium was taken up in debates among physiologists and phoneticians about vowel production. Drawing upon the research of Stumpf, the physicist Dayton Clarence Miller, and the radio engineer Karl Willy Wagner of the 1910s and '20s, Trautwein argued that the vibrations generated by impulse (or shock) excitation that produced musical sounds were the electrical equivalent of the vibrations created by air traveling through the speech organs giving rise to the vowel sounds. The damped and decaying vibrations formed the formants, or the dominating overtones of a musical note or speech sound that determined its timbre. Such investigations were critical to radio broadcasting fidelity.

After initially focusing on the origins of German radio and the trautonium much like a convex lens, the second portion of the book behaves like a concave lens, radiating out to trace the various trajectories of the instrument. Both Trautwein and Sala realized shortly after the National Socialists' rise to power that they needed to convince the Nazis to support their work on the trautonium, as detailed in chapter 6. Iverson has written on the Nazi past of physicists and engineers working on electronic music after World War II, particularly Werner Meyer-Eppler.[39] Trautwein was no exception. While Sala never joined the Nazi Party, he possessed business savvy and certainly benefited from the party's patronage. Goebbels thought that the trautonium could serve as a perfect instrument for Hausmusik and was delighted to hear about its potential use in mass rallies. He was deeply impressed by the instrument after being granted a private demonstration and performance by Sala in April 1935. The trautonium could play traditional works of Paganini, Beethoven, Mozart, and Bach for violin, flute, cello, and organ. Here imitation was key. But more modern pieces by Harald Genzmer and Ferrucio Busoni—the Italian composer who influenced the Italian Futurists, many of whom were sympathetic to fascism and supporters of Benito Mussolini, were also featured. A number of critics, amazed by the range of tone colors that the instrument generated, labeled it a "Wunderinstrument." Chapter 6 also tells the story about the role a particular engineer, namely Trautwein, played in supporting the Third Reich. In that respect, he was typical of many German engineers during the period.

After the war, Trautwein receded into the background, as discussed in chapter 7. He did, however, write a number of essays reflecting on the engineer's role in German culture. Reminiscent of the attempts by natural scientists and engineers to redeem themselves before a skeptical public after the humiliating defeat of World War I, Trautwein wished to carve out a space for electrical engineers contributing to music with a hope of restoring his and his discipline's reputation with the newly created state of the Federal Republic of Germany and its intellectuals. Sala, on the other hand, continued to experiment with the instrument. While he still used the trautonium to imitate more conventional instruments, he branched out into other genres, thereby enabling his instrument to unleash unique, futuristic, and uncanny timbres employed in radio dramas and theater pieces. The concert trautonium was often used by composers who wished to make a conscious break with the Nazis' legacy, for example Brecht and Paul Dessau's operas, *Die Verurteilung des Lukullus* (*The Condemnation of Lucullus*) and *Deutsches Miserere*. Sala's final invention, the mixture trautonium of 1952, produced sound effects for operas, such as the Grail bells in Richard Wagner's *Parsifal* and the hammering sounds of the goldsmith in *Das Rheingold*. While some critics praised the instrument's versatility, others were troubled by the monstrous cacophony it produced. By the time he retired in the 1990s, Sala had played his mixture trautonium for over one hundred radio and television commercials and three hundred films, a number of which were commissioned by various chemical and Big Pharma companies in West Germany.

The music the trautonium played was not the only type of new music filling the airwaves in postwar Europe. Pierre Schaeffer and his *musique concrète* cohorts in Paris were creating new types of sounds by manipulating tape. Meyer-Eppler and his colleagues, Robert Beyer and Herbert Eimert, created the Studio for Electronic Music in Cologne. As discussed in chapter 8, Trautwein and Sala competed with these groups, particularly the Cologne Studio, to help preserve their contributions and legacy to postwar music. Sala in particular thought hard about the ways that tape recording increased the types of tone colors and sounds that could be combined, as tape provided a new experimental system for the instrument. The competition was fierce, and the trautonium featured prominently in the crucial debates, such as the role of the performer as interpreter of a composition, the importance of experimentation and improvisation with the instrument while playing, and the use of tape recording while performing. Would the future of music consist of instruments made of vacuum tubes and electric circuits, or (later) transistors? Would electronic music be successful in eliminating the human in music altogether?

This is a story about twentieth-century science and the social spaces where it occurred, the metropolises. By the late nineteenth century, science had been reorganized and had become slightly more egalitarian due to less social stratification. While women and people of color were still massively underrepresented, many more people were participating in science compared to earlier in the century. Much of that was due to the rise of the engineering disciplines as well as heavy industry, and World War I certainly accelerated the transformation. Metropolises such as Berlin provided a venue where a vast multitude of skills and expertise from newly created industries and disciplines, or previously existing ones that had had no contact with each other, began to combine in extremely fecund collaborations. Physicists and electrical engineers were now working with physiologists and musicians. We all know about "Big Science"; however, this particular story is about the relationships between science, technology, and music—their complexities as well as their interrelatedness—that generated explicit collaborations that enabled the creation of new aesthetic concepts and technical possibilities.

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