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Resynthesis as a Form of Imitation - A Powerful Compositional Technique

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ABSTRACT

Karlheinz Stockhausen used this compositional technique as early as 1955 in his *Gesang der Jünglinge*, and yet it still seems new and fresh in today's premières. The technique that has lost none of its relevance for over 60 years is resynthesis. In contrast to (sound) synthesis, i.e. the method of creating artificial sounds, resynthesis attempts to reproduce an existing sound, i.e. to imitate it. Resynthesis is therefore a form of imitation. The principle is simple: you take an original sound emanating from an original sound source, recreate it with another sound source and then develop it further in a way that would not have been possible with the original sound source. This enables a creative development of the sound that goes beyond the possibilities of the original source.

In this thesis, the technique of resynthesis is placed in the context of imitation and mimesis. The emergence of resynthesis is examined further in a historical chronology before resynthesis and the associated analysis are the topic. Finally, I list some tools and software and end with a conclusion.

ABSTRACT

Karlheinz Stockhausen verwendete diese Kompositionstechnik bereits 1955 in seinem *Gesang der Jünglinge*, und doch wirkt sie in den heutigen Uraufführungen immer noch neu und frisch. Die Technik, die seit über 60 Jahren nichts von ihrer Aktualität verloren hat, ist die Resynthese. Im Gegensatz zur (Klang-)Synthese, also der Methode, künstliche Klänge zu erzeugen, versucht die Resynthese, einen vorhandenen Klang zu reproduzieren, also zu imitieren. Resynthese ist also eine Form der Nachahmung. Das Prinzip ist einfach: Man nimmt einen Originalklang, der von einer Originalklangquelle ausgeht, bildet ihn mit einer anderen Klangquelle nach und entwickelt ihn dann in einer Weise weiter, die mit der Originalklangquelle nicht möglich gewesen wäre. Dies ermöglicht eine kreative Entwicklung des Klangs, die über die Möglichkeiten der ursprünglichen Quelle hinausgeht.

In dieser Arbeit wird die Technik der Resynthese in den Kontext von Imitation und Mimesis gestellt. Die Entstehung der Resynthese wird in einer historischen Chronologie weiter untersucht, bevor die Resynthese und die damit verbundene Analyse das Thema sind. Abschließend führe ich einige Werkzeuge und Software auf und schließe mit einem Fazit.

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Chapter 1

INTRODUCTION

Imitation has been at the heart of art from the very beginning. With the new technical possibilities, musical imitation can even be a copy of the original through the use of resynthesis. Due to its ability to creatively utilise the parameters obtained through analysis, resynthesis offers a wide range of new possibilities.

Resynthesis is so original and free that it cannot be categorised in any era. It takes the technological tools of each era and uses them for its own purposes. In this way, it is able to be both contemporary and ancient at the same time.

This work does not provide a list of resynthesis algorithms or step-by-step instructions. Rather, it aims to illustrate the importance and possibilities of resynthesis and to put imitation methods of the past into a new context. The disadvantage that not every sound can be reproduced with the same type of resynthesis is at the same time the great advantage that such great variability in resynthesis is possible.

This work first describes the origin of imitation or mimesis with examples of different types of imitation. In an analysis section, the importance of precise prior analysis is explained before the pioneering role of spectralism is discussed further. The benefits and challenges of supporting software are then highlighted. The discussion of some pieces then shows the current limitations of resynthesis and where the future should be heading.

Chapter 2

IMITATION COMES FROM MIMESIS: A BRIEF EXCURSION INTO PHILOSOPHY

This chapter is by no means a complete examination of mimesis and imitation in the context of philosophy and history. These are themes that have become apparent to me in the course of writing this thesis and I am only at the beginning of my research into them. They turn out to be so extensive that they cannot be fully dealt with in the context of this thesis. Nevertheless, I did not want to exclude them completely. However, I would like to point out that they are only intended to give a small insight and thus show that it would be valuable to investigate them further in a future work.

2.1 Origin

Mimesis is a fundamental core of art and comes from the Greek term *mīmeisthai* - to imitate (Sachs, 2016). For Plato and Aristotle, mimesis was the representation of nature, including human nature. In this period, it was reflected in the dramas. Mimesis is an important concept in the field of literary criticism and philosophy. In this work we focus on the term in relation to music and only touch on the subject of philosophy and literature in passing. While Plato was sceptical about the use of mimesis, especially when it was not used in an uplifting way that served the beautiful and the good, Aristotle was fully convinced of it and even wanted to culminate emotions in drama in all possible ways.

2.2 Jean-Baptiste le Rond d'Alembert (1717 - 1783)

Jean-Baptiste le Rond d'Alembert (1751) said that things that arouse unpleasant feelings become more pleasant when they are acted out than in reality, due to the distance that acting gives us.[1]He went on to write that in creativity there is a great degree of freedom between the truth and the arbitrariness of imitation. And specifically about music, he wrote that any music that describes nothing is simply noise[2] (d'Almebert, 1997).

[1] „Diejenigen Dinge aber, die bei wirklichem Erleben nur traurige oder stürmische Gefühle in uns erregen würden, wirken angenehmer in der nachahmenden Darstellung als in Wirklichkeit, weil ihre bloße Darbietung uns gerade in jenen entsprechenden Abstand (cette juste distance) zu ihnen bringt, der uns die Erregung zum Genuss, aber nicht zur inneren Unruhe werden lässt.“ - Jean-Baptiste le Rond d'Alembert

[2] „Toute Musique qui ne peint rien n'est que du bruit.“-Jean-Baptiste le Rond d'Alembert

2.3 Immanuel Kant (1724 - 1804)

For Immanuel Kant, the function of mimesis was not to copy a concrete representation, but to emphasise its essence in order to show its infinite beauty and strength. Around 1800, mimesis was replaced by empathy. Nevertheless, empathy also has mimetic qualities. It is not the object that is imitated, but the feelings of the observer.

2.4 Theodor W. Adorno (1903 - 1969)

Adorno says that art consists of *mimesis and construction* (Theodor W., 2003). Works of art draw material from reality and put it together in a different way to create a world in which the parts are not subordinate to the whole. And this material does not have to be beautiful. He said that art has the task of making the ugly its own. [3]

2.5 Wolfgang Welsch (1946 -)

In Wolfgang Welsch's *Immer nur der Mensch?* (Welsch, 2011) he writes that Plato's concept of mimesis is not imitation as a copy of the thing itself, but means that imitation is a deception of appearance and being. It is an "to-do-as-if".[4] There is a difference between the thing and its imitation.

2.6 Reflections on semantics

When we imitate a sound, we must immediately deal with the semantics of the sound. When we hear a warning signal, for example, we get the feeling that we want to do something. When we hear the noise of road traffic, we associate it with negative feelings. When we hear the sound of ocean waves, we associate ourselves with positive feelings. Clemens Gadenstätter says that dealing with such sounds requires compositional techniques that break through this codification of hearing. The music should simultaneously reveal the code, which thus remains effective, but also undo it, change and dissolve the ways of perceiving the objects and the contexts in which they are embedded, and thus also transform their meaning into a

[3] "Kunst muss das als hässlich Verfemte zu ihrer Sache machen . . . , um im Hässlichen die Welt zu denunzieren" - Theodor W. Adorno

[4] "Von daher liegt eine Bemerkung zu Platons Begriff der mimesis nahe. Dieser Begriff meint nicht so sehr, dass ein Abbild gegeben wird, das der Sache mehr oder weniger ähnlich ist, sondern meint den grundsätzlichen Betrug, dass überhaupt ein Abbild statt der Sache gegeben und dabei doch für eine Gegenwärtigung der Sache selbst ausgegeben wird. Gerade dieses Quidproquo, diese Gaukelei, diesen Schwindel, den Schein an die Stelle des Seins zu setzen und dafür gelten zu lassen, hat Platon im Auge, wenn er von künstlerischer mimesis spricht. Mimesis zielt nicht auf ein Abbild-Theorem, sondern brandmarkt das So-tun-als-ob aller sogenarmten Nachahmung."-Wolfgang Welsch

different form and content through a changed way of listening (Gadenstätter, 2007). While earlier composers were simply unable to use the original itself, contemporary composers are able to do so, they can simply use original recordings. Despite this possibility, Clemens Gadenstätter actively chooses to change this sound material, to musicalise it. He takes selected characteristics of the original sound and transforms them into musical material or places them in a different context. By changing the material, the associated memories and emotions and the inner qualities can also be changed. This interesting space between the musical object invoking the memory and the intended sound heard purely as music is an intensive, creative space for the compositional process.

From my point of view, ideologically speaking, Clemens Gadenstätter is exactly between *Musique Concrete* (Schaeffer, 1973), which has set itself the task of distorting the original sounds beyond recognition, and the work of Luc Ferrari, who works specifically with the feelings and memories associated with the sounds. Luc Ferrari even says that he would never exert his will on the sound. Cutting, mixing and assembling sound seems absurd to him (Robindore, 1998). And that is exactly the space I find myself in when working with resynthesis. This specific grey area between reality and unnaturalness, between semantic and pure sound.

Chapter 3

THE EMERGENCE OF RESYNTHESIS

3.1 An attempt at categorisation

Nicolas Donin proposes to categorise different forms of resynthesis (Donin, 2016). There are several approaches to categorisation. One approach could be based on the nature of the original sound. In today's performance practise, however, categorisation according to terms such as natural, environmental or instrumental is problematic, as environmental sounds are integrated into scores. Defining clear boundaries would be a challenge. Instead, the categories could be defined in such a way that original sounds also occur in the piece and original sounds do not occur in the piece. Alternatively, the categorisation could also focus on the method of resynthesis: Resynthesis by Instruments, Resynthesis by Computer and Intuitive Resynthesis. A potential problem with this approach is the ambiguity of the second category. For example, where would a sound analysed by a computer and then transcribed for sine wave oscillators belong?

Another possible categorisation is based on the method of analysis: analysed by intuition and analysed by spectral analysis. In this method, transcribed birdsongs would be grouped with imitations of instruments that also appear in the piece, resulting in pieces from different eras falling into the same category.

In view of this complexity, I propose to dispense with categorisation altogether and concentrate instead on presenting the chronological development that led to the resynthesis.

3.2 Until 1950

Without the use of computers, the term imitation seems more appropriate than resynthesis. Even instruments were built to imitate human voices (Tai et al., 2018). The first modern violins from the 16th century were able to produce the same tonal characteristics as human voices, summarises a group of researchers from the University of Taiwan. Some examples of the imitation of sounds not found in the piece in the composition are (O'Callaghan, 2015):

- 1528: Clément Janequin's *Le chant des oiseaux*. The singers imitate birdsong.

- 1808: Beethoven's *Symphony No. 6* . environmental sounds.
- 1830: Berlioz' *Symphonie Fantastique*. Ambient sounds.
- 1940: Messiaen's *Quatuor pour la fin du temps*. Bird calls.

The only way for composers to imitate was to transcribe what they heard and collaborate with instrumentalists to create these sounds from outside the classical repertoire. With the advent of technology, a new era dawned.

3.3 From 1950: Cologne and the sine wave generators

Since Fourier in the early 19th century, it has been known that every possible signal can be reconstructed by the sum of sine functions. Karlheinz Stockhausen applied this knowledge when he came to the WDR studio in Cologne. He was interested in music that was organised in all aspects. With a series of sine generators, he was able to construct timbres. With him in the studio was Werner Meyer-Eppler, who had a strong interest in phonetics. This is how Stockhausen came up with the idea of resynthesising a boy's voice. *Gesang der Jünglinge* was born. At that time, neither computer-aided analysis nor resynthesis was possible. He did everything by hand and in a very labour-intensive way. The boy singer was recorded while listening to the sine waves through headphones.

3.4 Around 1960

Nicolas Donin writes in (Donin, 2016) that the first instrumental resynthesis piece he knows is the *Le son d'une voix* by Francois-Bernard Mache (1964). Here, Mache recorded himself reading and closely studied a spectrographic representation of the result. His transcription is shown in figure 3.1. For the orchestration, he used percussion gestures for consonants and various harmonic instruments for vowels.

3.5 From 1970: Spectralism as a precursor of resynthesis

Spectralism emerged in the late 20th century as a particular movement within contemporary classical music, associated in particular with composers such as Gérard Grisey and Tristan Murail. The central idea behind spectralism is the exploration and manipulation of the spectral content of sound, focusing on the analysis and synthesis of harmonic components (Grisey and Fineberg, 2000). Composers attempted to create intricate sound structures by using mathematical models derived from spectral analysis of acoustic phenomena. This focus on the spectral aspects of sound paved the way for the development of resynthesis.

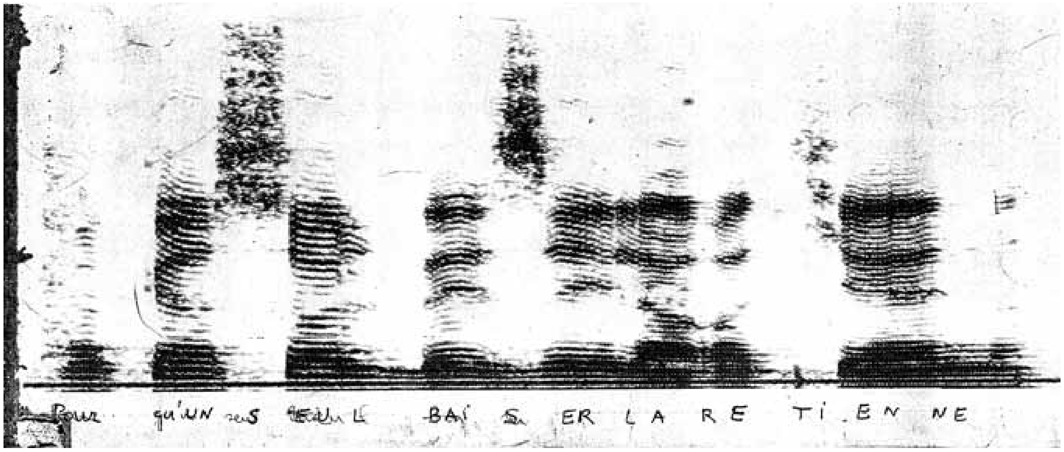

Figure 3.1: Francois-Bernard Mache's transcription for *Le son d'une voix* (Donin, 2016)

Although spectralism concentrates more on the phenomenology of harmonic series than on the semantics of sound (Wannamaker, 2008), it imitates nature itself and natural sounds. Otherwise, other frequencies than exactly the multiples of the fundamental frequency could have been used.And in some pieces, e.g. in Tristan Murail's *Mémoire/Erosion*, concrete sounds of origin are imitated (Anderson, 2001).

In resynthesis, complex sounds are recreated by synthesising their individual spectral components, allowing composers to model and manipulate the sonic properties of the sound source. Spectralism, with its great attention to the sound spectrum, laid the foundation for the innovative approach of resynthesis. It provides composers with a powerful tool for creating the complex and nuanced textures that characterise contemporary electronic and electroacoustic music.

3.6 Acoustic instruments: From 1980

Barlow developed Synthrumentation (Poller, 2015). Synthrumentation is a technique for resynthesising speech using acoustic instruments. He used this technique in his piece *Im Januar am Nil*, 1981. Barlow received support from the Institute of Phonetics at the University of Cologne and analysed the voice in detail. Similar to Barlow, the following pieces (Donin, 2016) were created: Thomas Hummel's Nicanor (1996–97) for orchestra, Claudy Malherbe's Locus (1997) for real voice and virtual voices and Jonathan Harvey's Speakings (2008) for orchestra. The listener is confronted with a ghostly voice emerging from the orchestra, but it is not like spectralism. Specific characteristics of the voice are projected onto the orchestra.

3.7 From 2000: More technology

While analysing and resynthesising took the pioneers a lot of time and effort, technical developments make the process much easier today. in 2008, Aaron Einbond composed his *Beside Oneself* with the help of the software *CataRT*. I will explain the software in more detail in the chapter 5.1. The piece is written for viola and live electronics. Einbond takes certain moments of the viola playing and plays them back with the live electronics in different ways; sometimes it just holds the moment of the viola and plays it longer while the viola continues, sometimes it changes the timbre, but it is always strongly connected. The piece is available online (Einbond, 2008).

3.8 Intermediate time in electronic music: physical modelling

The most obvious technique for resynthesising sounds from the real world is physical modelling synthesis. With this technique it is possible to simulate natural sounds and develop them in an unnatural way. You could call it a distortion of reality and play with this grey area between reality and synthetics. For an impressive list of pieces developed with physical modelling, I refer you to (Chafe, 2004). in 1999 Hans Tutschku composed *Eikasia*. During the realisation he compared synthetic and real sounds and from this starting point achieved this broad sound scale from abstract to real sounds. For the piece *Things She Carried*, Paul Lansky uses physical models of instruments with physical parameters that were never built, such as 20-foot-long flutes with a diameter of 3 feet (Clark, 1997). For this piece he used STK Flute (CCRMA Stanford, 2024a). In Matthew Burtner's piece *S-Morphe-S* (2002), the acoustics of a soprano saxophone and a singing bowl are fused together. In his piece *Pipe Dream* (2003), Gary Scavone works in a very subtle way between a familiar, real saxophone and something very similar, but new and unnatural. He used an STK toolkit from CCRMA Stanford (CCRMA Stanford, 2024b).

3.9 From 2020

Clara Iannotta also used resynthesis techniques in *where the dark earth bends* (Iannotta, 2022). She chose the repeated audio signal room recording of another sound as the original sound, following the example of Alvin Lucier's *I'm sitting in a Room*. With great attention to detail, precise determination of frequency pitches and the invention of new instruments, Clara Iannotta created this resynthesis piece (*Discourse- Impuls* 2024).

Although her imitation comes impressively close to the original sound, it can always be distinguished from the original sound. Algorithmic resynthesis can overcome this problem and imitate an original sound exactly. At the same time, it is able to manipulate the sound in a very targeted way. And in this way it has the power to play with this fine line between real and unnatural, semantic and free.

Chapter 4

RESYNTHESIS

Apart from listening, the best way to analyse a sound is to look at its frequency spectrum. Every sound, every hiss, every noise can be composed of a sum of sine tones with different amplitudes. The realisation that harmonic sounds consist of fundamental tones and their multiples led to spectralism with Gerard Grisey. To this day, sounds consisting of partials with random amplitudes are combined in concert halls in an attempt to hit the exact frequencies. This is undoubtedly impressive, especially as these frequencies do not correspond to the notes on the staff. Spectralism has thus shown that it is possible to synthesise a frequency spectrum. It is a method of sound synthesis and therefore a precursor to resynthesis. Resynthesis goes one step further. The main reason why the a of a violin sounds different from the a of a flute lies in the amplitudes of the overtones. The amplitudes are not coincidences; they imitate an original sound. While the determination of these individual amplitudes was still very time-consuming for Stockhausen, Clara Iannotta had it a little easier with the means available today. She used software to visualise the frequency spectrum, searched for the dominant frequencies and carried out a careful analysis. While such technical innovations are a help for the analysis part of the composition technique, software tools for resynthesis should be used with caution.

4.1 Analysis always comes first

Andy Farnell wrote: *Good sound design is more about analysis than synthesis* (Farnell, 2010). The most descriptive and intuitive way to analyse a sound is the time-frequency spectrogram. The spectrogram is the short-time Fourier transform of a sound. This means that the sound is broken down into short, overlapping chunks of about 30ms, where the chunks are called *windows*. Each window is Fourier transformed so that we get one amplitude value per frequency. When viewed across all windows, an image is obtained. The spectrogram is still the same as the one used by Mache in Figure 3.1. Today's spectrograms are still the same, but more colourful like Figure 4.1. In addition, today's software tools also offer a one-click display of frequency, note or midi information for more convenience.

Although spectrograms are very effective, they are not the only way to visualise a

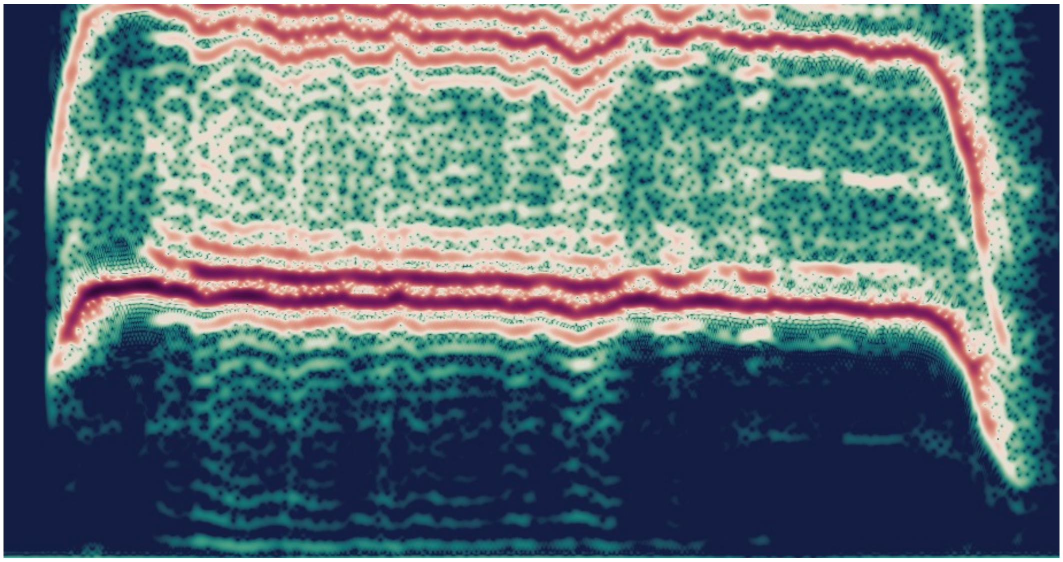

Figure 4.1: A Time-Frequency Spectrogram of a Scream, created with *Python - Librosa*, see chapter 5.1

sound. In signal processing, there is the field of *Music Information Retrieval*. This is also the basis for pattern recognition and machine learning, which will not be discussed further in this thesis. Depending on the sound to be analysed, there are a variety of parameters or so-called *features* that can be extracted from the sound. In general, it can be said that features that are suitable for pattern recognition are also quite suitable for signal visualisation. Speech signals, for example, can be well described by Mel Frequency Cepstral Coefficients or a Mel Spectrogram. These features work with the property of the way we perceive sound. The perceived distance between 300Hz and 303Hz is completely different from the perceived distance between 10000Hz and 10003Hz. The Mel filter bank takes advantage of this. I will not go into all the possible features, this would go beyond the scope of this work, instead I refer to (Wiering and Volk, 2022). If you are working with Python, you do not have to implement the functions yourself, there are various packages with already implemented algorithms. Some of these packages are listed in the 5.1 chapter.

But let us talk a little more about spectrograms. Extracting information from spectrograms requires some practise. What do we need to pay attention to? First of all, it's helpful to look at spectrograms of familiar sounds and pieces. For example, use *Audacity* (Audacity Developer Team, 2024) to view the spectrograms of audio files. Next, you need to answer a few questions: Is the sound harmonious? Is there any noise? In which frequency range is the noise? How is the energy of the signal distributed, both over time and frequency? What about attack, sustain and release? If a frequency persists, is there any variation? If a lot happens in a short time, it is often helpful to play the signal more slowly. A kick, for example, is not just a deep noise with a short attack. If you look closely, you will realise that it is a very fast downward sweep with a sharp attack. Ears can be trained to recognise distortion, compressors, allpass filters and so on. A trained ear is a great help and saves a lot of time when analysing.

4.2 Suitability of algorithms - maintaining the degree of freedom

I argue that resynthesis has retained its relevance and freshness to this day for two reasons: Firstly, it comes very close to imitation or mimesis and thus to the core of art, and secondly, it allows an incredible degree of freedom for creative work. For *Gesang der Jünglinge* Stockhausen worked through several steps, with every step leaving room for creativity. From selecting the vocal sounds to analysing them and adding each individual overtone, which was necessary due to the small number of sine wave generators, each step allowed a high degree of creative freedom. If the orchestration of *where the dark earth bends* had been done by a software like *Orchidea*, see chapter 5.1, published in 2022, it would not be the same piece. Software will never write in the score that the strings should paint polystyrene if no one has come up with this idea before. The close collaboration with the wind players and the joint development of the piece would have been lost. Not to mention the emotionality, the fragility and the tension.

Technological progress has already buried some compositional techniques by making simple reproduction possible, leading to boredom, as in the case of granular synthesis. But this is not yet the case with resynthesis. If the new technologies are used in a targeted way, but with enough freedom to intervene creatively, there is still enormous potential in this compositional technique.

In model-based signal processing, there are many legacy algorithms that are ideal for resynthesis. The term *model-based* is important here. This means that there is a theoretical model, for example the physical model of the violin. The model has many parameters, all of which have a meaning. If you change them, you can expect certain results. For example, if you change the length of a string, the pitch will change. For the piece *Lux Aeterna Unlimited* I used an algorithm package from speech signal processing, namely *Covarep* (Degottex et al., 2014), see chapter 5.1.

When the algorithm analyses a singing voice, you are then in possession of intuitive parameters such as pitch and amplitudes of the overtones. Under optimal conditions, the resynthesised sounds are indistinguishable from the original. This means that you can recreate the original sound perfectly and now have the parameters in your hands to shape the sound to your liking. Voices continue to develop into sounds that humans alone cannot produce. When you use the source-filter model to resynthesise the voice, you have separate ownership of the source, i.e. the fundamental frequency and overtone frequencies, and the filter, i.e. the degree of reduction of frequencies across the spectrum. Now the source can easily be replaced by other sounds and noises, as you can hear in my piece *Dies Irae*.

4.3 Resynthesis: Finding the best algorithm

There is no one best algorithm for every sound. The suitability of the algorithm depends on the sound itself. The fact that every sound can be modelled by summing a few sine tones does not mean that this is always the best way. This would have to be done every time the sound changes. And natural sounds are constantly changing, even if a tone is played or sung at the same volume for a few seconds.

Physical modelling algorithms make it possible to adjust the parameters for the size and material of the instrument. You can simulate an instrument that was never built. But you cannot directly build the sound itself. If you want a lower frequency, you have to think about which parameters you need to adjust to achieve this behaviour. The HMPD algorithm of *COVAREP* (Degottex et al., 2014) allows you to adjust the spectrum directly. However, it is not able to calculate sounds in real time. And you really need to know what you want to do with the signal. For the algorithm of a source-filter model, you need to create a database of filters and find source trajectories that are close to the natural model, which means a lot of analysis work.

4.4 Resynthesis: An example

To demonstrate the power of resynthesis and the importance of the degree of freedom, this section shows an example. A voice was recorded that sings from low to high. The time-frequency spectrogram is shown in Figure 4.2. The recorded signal was analysed and resynthesised using the algorithm *Harmonic Model And Phase Distortion* by *Covarep* (Degottex et al., 2014), see chapter 5.1.

Two things are available after resynthesis: The resynthesis as an audio file with its spectrogram in 4.3, and a handful of parameters, such as fundamental frequency and spectral envelope. Since we are in possession of these parameters, they can now be

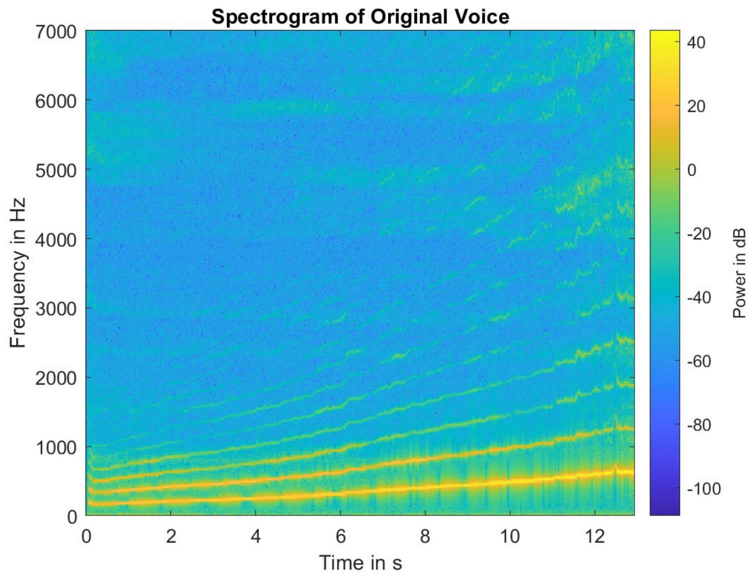

Figure 4.2: Spectrogram of a Recorded Voice Singing from Deep To High

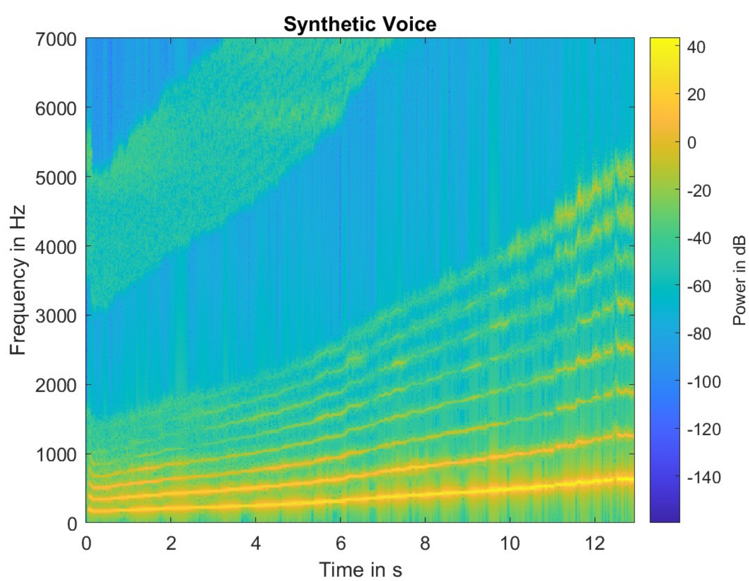

Figure 4.3: Spectrogram of the Resynthesis of the Recorded Voice Singing from Deep To High

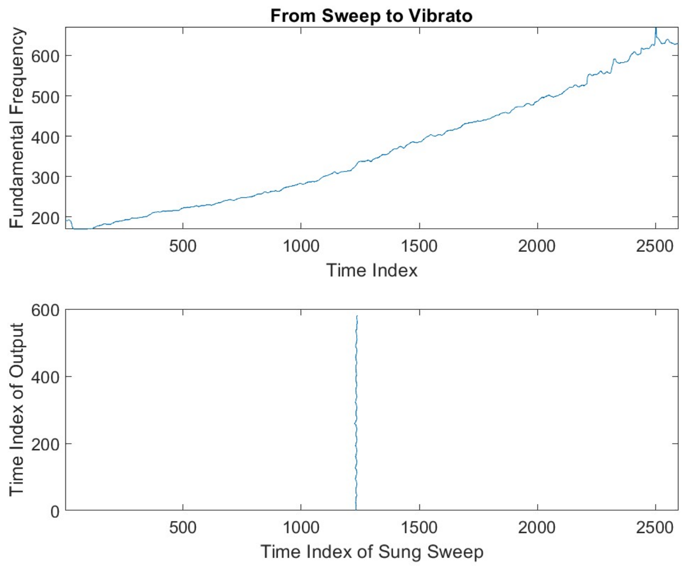

Figure 4.4: Fundamental Frequency and Time Index Mapping of the Recording

changed immediately before resynthesis to create something new. For example, we can make the voice sing a vibrato. To do this, we select the desired frequencies as shown in figure 4.4. The upper figure shows the fundamental frequency over time of the original recording. The lower figure shows the time index of the recorded voice compared to the time index of the output. This means that for each time step of the output, we select a desired fundamental frequency from the upper figure. With these indices in a vector, the signal can be resynthesised again. The spectrogram of the new signal is shown in Figure 4.5. This would also have been possible without the relatively complicated *HMPD* algorithm by simply rearranging the spectrogram and performing an inverse Fourier transform with a subsequent overlapaddition process. The algorithm has other advantages as well. If we now want to change the partials, this is now also possible. You can hear this for example in my piece *Lux Aeterna Unlimited*. We could also change the vibrato voice into a cello. The original spectrogram of the cello can be found in 4.6, its resynthesis in 4.7.

And the fusion of voice and cello you can see in 4.8.

With the parameters in hand, the signal can now be moulded and shaped as desired. The scope for creativity is immense.

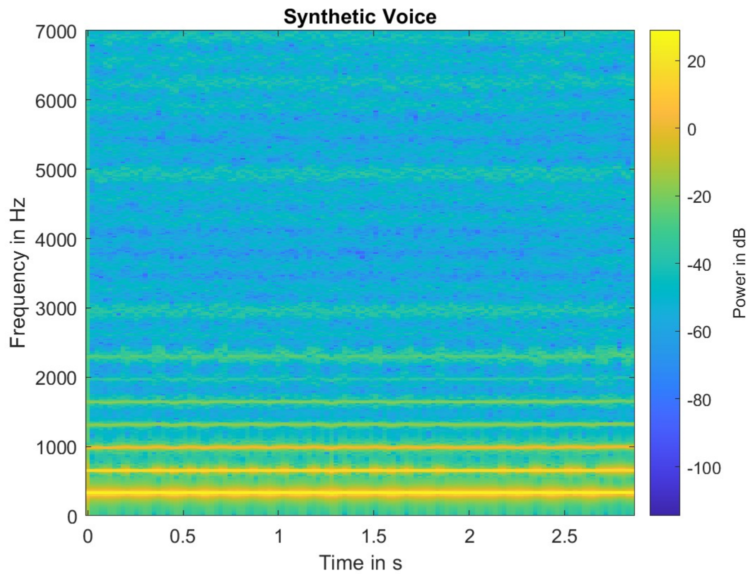

Figure 4.5: Spectrogram of the new Vibrato-Resynthesis

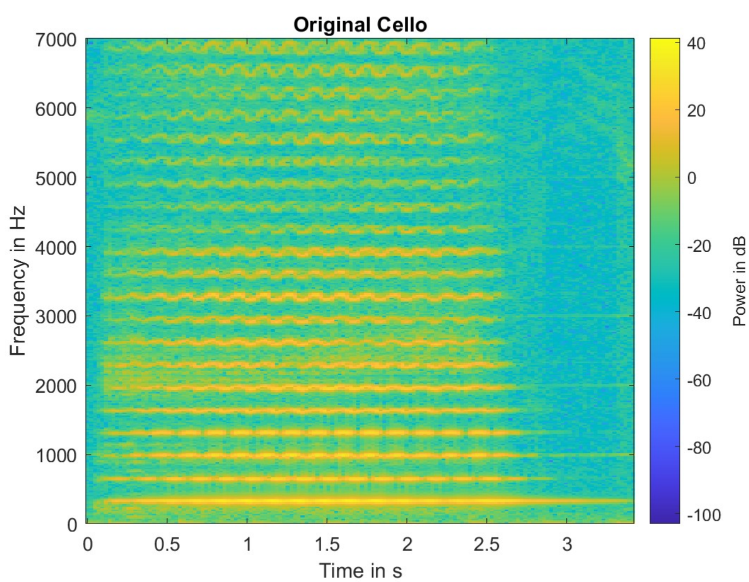

Figure 4.6: Spectrogram of a Cello Vibrato

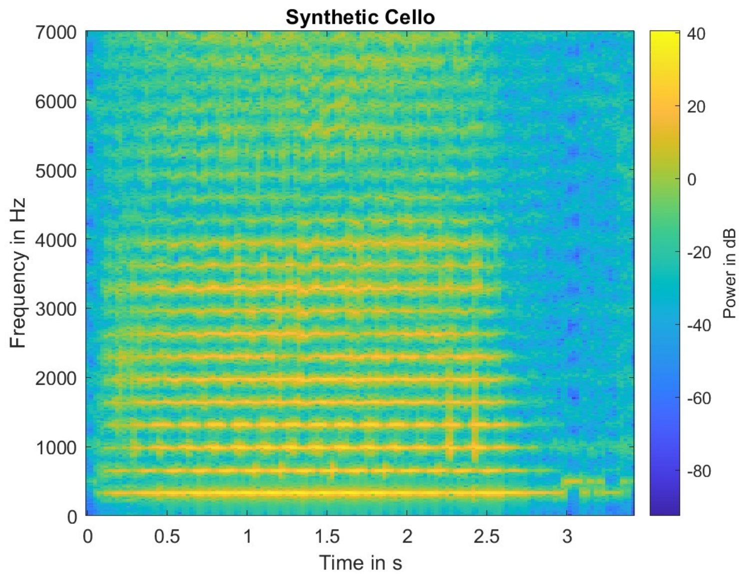

Figure 4.7: Spectrogram of a Cello Vibrato Resynthesis

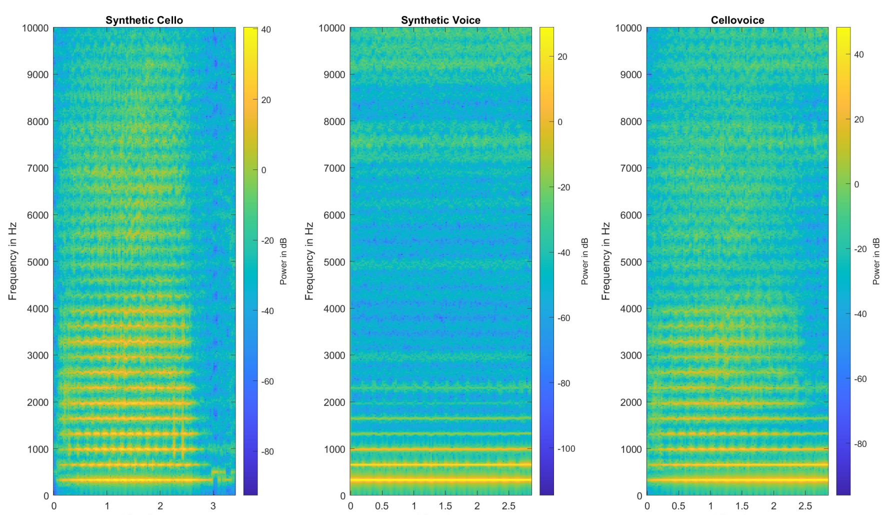

Figure 4.8: Spectrogram: From Cello to Voice

4.5 The creative aspect of resynthesis in an example

My piece *Im innersten Gemüt* (Anna Maly, 2024) is about the text of Shakespeare's *Hamlet*. The semantics of a spoken text, especially the text of Hamlet, are so strong that any sound around it immediately becomes a faint background. So I had to merge the language with the sound in such a way that they could alternate. The first sentence *Ihr Auge nass, Bestürzung in den Mienen, gebrochne Stimm, und ihre ganze Haltung gefügt nach ihrem Sinn.* is so strong, every word of it, how the words are arranged and how the beginning of the sentence draws the listener towards the end. I wanted to reflect this perfection, this drawing, this attention to detail in the sound. It was not possible to do this in the same moments, the semantics were too strong. So I had to blend between the pure sound and the semantics of the words. So I took the beginning of the first word, the *I* of *Ihr* and made it very long. That's how I turned it into sound. I merged it with the sounds of the flutes. The flutes are also very strong, with strong beginnings, strong endings and strong pauses, just like in the words. The *ss* becomes a sound again and is interrupted by the next word. It is a perfect interplay between the art of sound sculpture and the setting of words to music.

With the techniques of resynthesis, I was able to transfer the perfection of words into music. I was able to determine the fundamental and overtones, the speed of the sounds, their entire spectrum, I was able to carry out this detailed working practise, without randomness, only with precise shaping according to my will.

Chapter 5

PRACTICAL IMPLEMENTATION

5.1 Tools and Software

The following list describes some available software to show what is technically possible or common today, and is of course not exhaustive. The description of some of these programs is borrowed from (O'Callaghan, 2012) and (Chafe, 2004).

- *AudioSculpt* (from IRCAM): Generates markers for sample information and quantises the spectral information into a certain number of pitch values.
- *OpenMusic* (from IRCAM): Directly imports *AudioSculpt* information to manipulate it and bring it into notation.
- *SPEAR* (from Michael Klingbeil): Partial tracking analysis. Only for visualisation, not for notation.
- *Orchidea* (by IRCAM): The predecessors were *Orchidée* and *Ato-ms*. Compares a target sound with a large sample bank of orchestral instruments and searches for the best match. The result is a series of solutions that can be customised by parameters. Each solution consists of a set of notations and audio samples. (IRCAM, 2024b)
- *Modalys* (from IRCAM): Modalys is a tool for creating virtual musical instruments with physical models that play in real time (IRCAM, 2024a)
- *STK Flute* (from CCRMA Stanford): Physical modelling of flutes (CCRMA Stanford, 2024a).
- *STK Saxofony* (from CCRMA Stanford): Physical modelling of saxophones (CCRMA Stanford, 2024b).

While these software tools offer convenient operation, especially for composers who do not come from the field of signal processing, it is also possible to delve deeper into the subject matter and use the signal processing tools. This is possible with the following software tools, for example:

- *MATLAB - Voicebox*: Implemented speech processing algorithms such as linear predictive coding, spectral distances and so on.
- *MATLAB - RASTAMAT*: Can calculate Mel Cepstral Coefficients, Cepstrum and so on.
- *MATLAB - Covarep*: A special repository for voice analysis. Can analyse the voice and then resynthesise it (Degottex et al., 2014).
- *Python - Librosa*: Basic audio processing algorithms such as spectrogram and other standard functions for music information retrieval.
- *Python - Audio-Similarity*: Calculates the similarity rate in terms of rhythm, energy, perception and other parameters.
- *Python - Pymus*: A Python library with several tools for automatic music analysis. Special focus is on algorithms for analysing melodies in audio recordings of musical instruments.
- *Python - Scamp*: A computer-assisted composition framework for MusicXML and sound output with possible MIDI instrument connection.
- *LilyPond*: A text-based score software. Ideal for combined use with a programming language that can easily output text that lilypond can convert into a convenient score.

5.2 Real-time manipulation and resynthesis

The proposed resynthesis algorithms in chapter 4.4 also have a disadvantage. The resynthesis process is too computationally intensive for real-time processing. Nevertheless, it is possible to analyse the signals before execution and use this knowledge live. Some of the algorithms listed can also be played back live. The challenges in terms of performance are discussed below.

5.3 Challenges and solutions

When a singer's voice has been analysed at different pitches, it is obvious to take a tone frequency and a spectral envelope, i.e. the amplitudes of the overtones, and use them to synthesise a singing voice. The result is a horribly synthetic sound. A deeper look into the analysis shows that even professional singers vary the pitch over time, even if only slightly. And with every change in pitch comes a slightly altered spectral envelope. These small variations make a sung voice sound natural.

There are various solutions for achieving this behaviour during resynthesis. Due to the small amount of data, I decided to write a database with one spectral envelope per recognised pitch for the mapping. During resynthesis, every time the frequency of the pitch changes, the spectral envelope also changes and suddenly we have a natural, purely synthetic voice.

If you take a closer look at Clara Iannotta's piece *dead wasps in a jam jar*, you can perform her realisation of the sine waves in different ways. The highlights of the piece are the moments when the strings play a note and the sine waves begin to play fluently. This is done with so much care that it is impossible to tell where the cello ends and the sine wave begins. If the sine waves do not exactly match the fundamental frequencies of the strings, the piece would not work. So either the strings have to play so precisely that the pre-programmed frequency matches perfectly. Or an algorithm searches for the exact frequency in a predefined range. The instrumentalists could also wear headphones to provide orientation. Another problem is the radiation characteristics of the loudspeakers. A real instrument can always be correctly determined by comparing it with the same sound coming from a loudspeaker. The loudspeaker changes the signal and radiates differently. If it only reproduces a sine wave, this is not a big problem. A sine wave has no upper frequencies or overtones, it only has a fundamental frequency. It therefore only has one parameter: the amplitude. If the loudspeakers are to play something more complex, where the similarity to the instruments on stage is important, it is advisable to amplify the instruments as well. Then the timbre of the instrument matches the timbre of the loudspeaker better. What sounds simple here is difficult in practise. Good sound engineers cannot be overestimated. A detailed sound check is obligatory. And always consider the room acoustics when it is filled with an audience. This requires careful and experienced sound engineers. In this particular role, the sound engineer's craft is so important that he/she takes on more of a musician's role.

Chapter 6

CONCLUSION

To summarise, the exploration of resynthesis as a form of imitation has not only illuminated its historical significance, from its beginnings in Karlheinz Stockhausen's Gesang der Jünglinge to contemporary works such as my *Im innersten Gemüt*, but has also underlined its enduring power as a unique compositional technique. As we traverse the landscape of resynthesis, the convergence of art and technology becomes ever more apparent, opening up new vistas for musical expression.

The journey through this work has highlighted the central role of analysis in understanding the parameters of the original sound and shaping the resynthesised result. While resynthesis thrives on the principles of imitation, it is careful analysis that serves as a compass, guiding composers through the intricate process of reproducing and renewing existing sounds.

The future of resynthesis seems limitless, fuelled by the rapid pace of technological advancement. As we stand at the intersection of art and science, the potential for resynthesis to shape the landscape of musical composition is truly exciting. The ever-expanding range of software and tools discussed in Chapter 5.1 offers composers a range of opportunities to push the boundaries of sonic exploration.

Beyond the technical aspects, resynthesis invites us to reflect on its broader implications for the development of musical styles. Its seamless integration into contemporary genres and experimental compositions suggests that resynthesis is not just a historical artefact, but a living, breathing force that continues to influence the evolution of music. And what should not go unmentioned here is the ability to combine contemporary music for chamber ensembles with contemporary electro-acoustic music.

When thinking about the future, one must consider the delicate balance between technological tools and artistic creativity. As technology evolves, composers are faced with the task of harnessing its possibilities while preserving the essence of creativity that defines musical expression.

In essence, resynthesis is not just a compositional technique, but also a catalyst for innovation, inviting composers to explore uncharted territories and redefine the boundaries of sound art. At the end of this exploration, the journey of resynthesis continues, promising exciting possibilities and contributions to the ever-evolving landscape of musical composition.

In the course of the work, a number of themes have emerged that would be worthy of further investigation. Firstly, the philosophical and historical aspect of imitation was only touched upon in passing. I am not an expert in this field and there is still some catching up to do. On the other hand, there is the part of the analysis that relates to the technical side, which could be analysed in more detail. Depending on the type of sound, other methods of analysis might be appropriate. The same applies to resynthesis. The artistic aspect should also be analysed in more detail: What transferred ideas can be expressed with resynthesis? Piece analyses could also be of great value for this part. Nevertheless, resynthesis as a method of imitation could be placed in its historical context and the possibilities of the latest technologies in resynthesis could be demonstrated.

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Appendix A

AI USED IN THIS WORK

For this thesis I used the website *deepl.com* for the translation from German into English and *instatext.io* for the native language translation. The first version of my conclusion was written with chat.openai.com, but heavily revised.