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Bachelor's thesis

# NÁZEV PŘÍKLADNÉ ZÁVĚREČNÉ PRÁCE

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March 26, 2022

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# Declaration

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# Abstrakt

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# Abstract

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# Acronyms

| | |
|---|---|
| DFA | Deterministic Finite Automaton |
| FA | Finite Automaton |
| LPS | Labelled Prüfer Sequence |
| NFA | Nondeterministic Finite Automaton |
| NPS | Numbered Prüfer Sequence |
| XML | Extensible Markup Language |
| XPath | XML Path Language |
| XSLT | eXtensible Stylesheet Language Transformations |
| W3C | World Wide Web Consortium |

# Chapter 1

# Introduction

Imagine a party. You can hear a variety of sounds: music in the background, conversations between people, noises of somebody coughing, maybe even a dog barking outside... These sounds merge into a single stream that approaches your ears by vibrations in the air and then goes through different physical, biological and psychoacoustical processes to finally come in a form of electrical impulses to the brain. Despite all these sounds from different sources are mixed on the way to your ears, the brain can segregate one (or several) of them. You can focus your hearing on these "target" sounds and separate them from the complex mixture, leaving other sounds in the background. This phenomenon has been described as a "cocktail party effect", and the process of integrating separate sounds into meaningful streams, or "auditory objects" – auditory scene analysis, or ASA.

In machine perception — specifically in machine hearing — a related concept is referred to as Computational ASA (CASA) and is tightly connected to the fields of sound recognition and digital signal processing. CASA systems indeed aim to separate sounds from mixtures, but they differ from BSS (blind source separation) systems in that they try to do this in a way a human ear does. Being based on and trying to combine works from different fields of science, CASA systems can bring new solutions and insights to the complex problem of signal separation.

The main objective for this thesis is to describe the principles and goals of CASA, existing applications and approaches. Another objective is to practically apply the theoretical knowledge and implement a simple CASA system to separate monophonic music from noise. But before all of this, since this thesis is made for an IT-oriented audience, it is needed to make a brief introduction to the underlying physics and biology.

Thus, the thesis is structured as follows:

Firstly, physical background theory will be provided, including an introduction to what a sound is. Since the implemented system from the practical part aims to segregate music from noise, a special focus in this part will be made on describing harmonic sounds and pitch perception.

Secondly, having in mind that CASA tries to mimic the human auditory system, a brief introduction to the biological structure of the human ear will be made. Here, auditory scene analysis according to Bregman will be introduced too.

Next, to cover the math in the implementation part, the basics of digital sound processing will be described. The related mathematical principles and functions used during the implementation will also be given some attention.

In the following chapter, having all the related theory in mind, an introduction to the main principles and goals of CASA will be made, along with an overview of its applications and selected models.

Then, in the practical part, the focus will be made on describing the implementation of specific parts of the CASA system built for this thesis (see attached medium).

Finally, an overview of the experiments made to test the implemented system will be provided.

# Chapter 2

# Physical Background

Before starting to ponder the structures of the human ear, it is necessary to understand the basics of how sounds work in the real world. It is safe to say that many people don't ask this question – they just make sounds or react to them, unconsciously knowing the outcomes. Human mind has already developed a deep understanding of which sounds are produced under different circumstances – you can easily say what to expect when somebody scratches a blackboard or rings a bell. Some could say that sounds are just "pressure waves that propagate through the air", but in reality, there is a lot of interesting and complex things beyond this definition to pay attention to. This chapter will introduce the reader to the underlying physics of sounds and some interesting related concepts. A special focus will be made on describing harmonic sounds, which are essential to understand to be able to work with music and pitch.

## 2.1 What a Sound Is

The definition of sound above, saying that it is just vibrations in the air, is hard to be called incorrect from the scientific point of view. Of course, there are improvements to be made: for example, that the sound can propagate not only through the air, but through any medium that has inert mass and is "elastic", or stiff, meaning that it will respond to forces applied to it. Making those corrections, it is also important to note that the definition above relates to sound as a physical phenomenon, but there is another definition that people use mostly in psychology and physiology, saying that the sound is a perception in the brain, or auditory sensation of the concept described above, or "an object of hearing". It is possible to argue about the question of "What Is Sound?" for a long time, as people still haven't come to a single definition and tend to mix the concepts [1], but in this thesis, the term "sound" will be used primarily in the first (physical) sense, unless specified differently.

For better understanding of how physical sound works, keep in mind the mass and elasticity of the air mentioned above. Overall, mass and elasticity (not only of the air, but of any medium) play a very important role in the related studies: mass-spring systems are a highly discussed topic, along with the type of oscillations they tend to have. Any object that can produce sounds may be considered a mass-spring system: a bell, a guitar string, or even air or water, which can be thought of as many small masses connected by invisible springs... This knowledge is quite staggering – in most cases, it is hard to imagine such system, because there could be no obvious mass nor elasticity. Consider an example for explaining resonant cavities: why a can of soda makes that clicking sound when it is being opened? The air is the answer. When you open the can, some parts of the air near its top act as a mass, and other parts near the bottom as a spring.

The pressure in the can drops, and the "spring" at the bottom tries to suck the "mass" back in, producing the expected sound [2].

Now, if you imagine the simplest of such systems, like the one on Figure 2.1, you can notice that when a particular force is applied to it, it tends to oscillate in a sinusoidal manner (due to some famous laws of physics, which will not be further discussed here). In fact, this can be applied to all mass-spring systems: they naturally "want" to vibrate in a sinusoidal fashion with a preferred frequency, called resonance frequency. Sinusoidal vibrations will be given more attention in Chapter 4

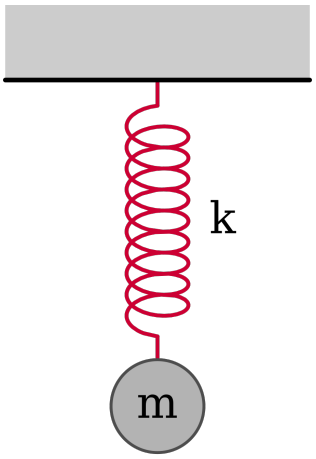



**Figure 2.1** A simple vertical mass-spring system. Taken from `https://commons.wikimedia.org/`

When someone talks about applying forces to objects, they can probably say that an impulse is delivered. In classical mechanics, impulse is a widely used concept, but for the purposes of this thesis, it is rather important to note how objects respond to impulses. When an impulse is delivered, the object starts to vibrate at all possible frequencies, but having in mind an understanding of resonance frequencies, it is safe to say that not all applied frequencies have equal amplitudes. Thus, some tones in the resulting sound tend to be louder, and others, if not completely silent, highly attenuated. In signal processing, the related concept is called an impulse response and can find some use when discussing digital filters in Chapter 4. The above-mentioned "chosen" frequencies will be described more in the next section.

Another essential topic to mention here is why sounds fade in time. This is again connected to the concept of mass-spring systems and the amplitudes of their vibrations. Usually, the greater these amplitudes are, the louder the resulting sound is, so if the amplitudes didn't become smaller, we would live in constant unbearable noise. In brief, the fading is caused by the resistance of the medium, in which the sound propagates, and the manner of this propagating. If you imagine air as it was described above — as many masses connected by invisible springs — the mechanics of the propagation becomes clear: the sound source pushes the closest mass near it, which due to elasticity pushes its neighbors and returns to its starting location. Then its neighbors, in turn, push their neighbors and return, and so on, until these vibrations come to your ears. The air masses must be pushed again and again for the sound to spread, so it tends to lose its strength along the way, and the further from its source it travels, the smaller the amplitudes of the vibrations become.

## 2.2 Harmonicity and Pitch

The conversation about how harmonics (or overtones) appear was already started in the previous section. In simple words, not all frequencies of the vibrations caused by delivering an impulse to an object keep their amplitudes for long. The ones that benefit the most from this phenomenon are harmonics, which are the periodic waves with frequencies that are positive integer multiplications of a specific frequency called fundamental (Figure 2.2). For example, if the fundamental frequency is 200 Hz, the corresponding harmonics are 400 Hz, 600 Hz, 800 Hz, 1 kHz and so on. Each harmonic can be labeled with a number – the fundamental frequency one is also called the 1st, so the wave with frequency of 1 kHz from the example above would be the fifth. However, the scientific notation for harmonics might be confusing – some authors refer to the fundamental frequency as $f_0$ (and the fifth harmonic would be $f_4$ in that case), others as $f_1$ (and $f_5$ respectively). In this thesis, fundamental frequency will be notated as $f_0$.

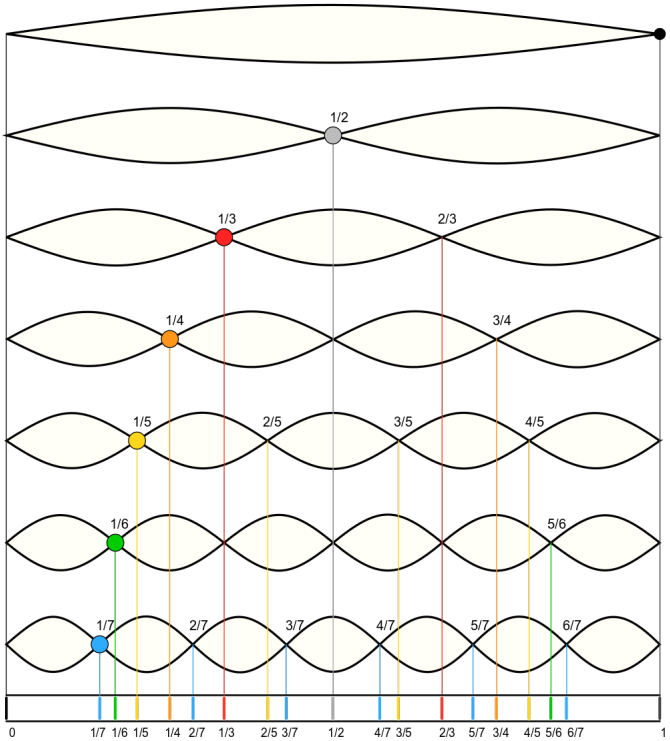



**Figure 2.2** First seven harmonics of a sound wave (or first seven modes of vibration of a string). Taken from `https://commons.wikimedia.org/`

Another explanation of how harmonics work might be found in [2]. When you pluck a guitar string, it doesn't vibrate only as a whole. The same string might be thought of as two halves, or three thirds, or even one hundred one hundreds, and that each part of it vibrates separately. So, when the string is plucked, all its harmonics are excited, and the resulting sound is not a pure tone, but a complex one. This behavior is often called "modes of vibration" and might be observed not only in strings, but also, for example, in sheets of metal.

The most interesting property of harmonics is that they are all periodic at their fundamental frequency. If you sum up any number of adjacent harmonics of a wave, the period of the resulting wave would be equal to the period of the fundamental. This property plays an impor-

tant role in the perception of pitch and is often used for its estimation in machine hearing systems.

Now, what is pitch exactly? To start using this term in the thesis, it is important to provide a clear definition, but in fact, there is none that is considered a standard. Two most widely used ones were given in [3]. The first one was provided by the American Standards Association (ASA) in 1960 with a reference to music – they defined pitch as *"that attribute of auditory sensation in terms of which sounds may be ordered on a musical scale"*. The second one was given by the American National Standards Institute (ANSI) in 1994 without a reference to music, saying that *"Pitch [is] that attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from low to high. Pitch depends primarily on the frequency content of the sound stimulus, but it also depends on the sound pressure and the waveform of the stimulus"*. For this thesis, it is enough to consider pitch as the auditory sensation mentioned in both definitions that can be ordered on a scale.

It is important to note that pitch is not a physical property of sound, but perceptual. When someone says "low pitch" or "high pitch", it is not certainly clear where this "low" or "high" is – low pitch for some people might be high for others. In the related studies of pitch perception in psychophysics, a term "just noticeable difference" (JND) is used, and there are references that humans can distinguish about 1 400 points on the pitch scale.

Pitch is often associated with fundamental frequency, though they it is not fully equivalent to it. Experiments have shown that for some short periodic sounds the perception of pitch might not appear at all, though it was clear that they had a fundamental frequency. On the other hand, there are reports saying that sounds with a missing fundamental (the ones made only from higher harmonics) could evoke the perception of pitch associated with the missing frequency, thus giving the illusion of what was not present in reality [2]. Either way, pitch is a major attribute used while describing tones in Western music, as well as is loudness, duration and timbre. Pitch also plays an important role in auditory grouping, given the fact that same sound sources tend to produce sounds of the same pitch. Auditory grouping in humans will be given more attention in Chapter 3.3.

# Chapter 3

# Biological Background

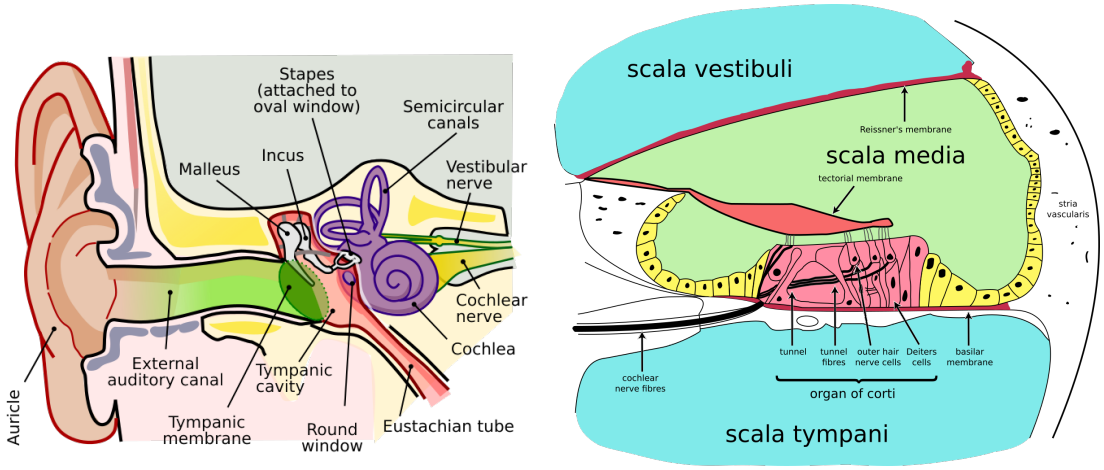
Sounds... For sure, they are one of the most important sources of information in our everyday life. By listening to them, one can describe what is happening around, understand how to react to occurring situations, or even tell if a danger is approaching, and it is time to take action. It is hard to imagine human sensation without hearing, but as easy as this may sound (no pun intended), the biology behind it is quite complicated. This chapter will introduce the reader to how sound as a mechanical phenomenon is converted to sound as perception and provide a basic overview of the structures in the human ear, along with the mechanical and neurobiological processes happening inside of them.

## 3.1 Outer and Middle Ear

At the beginning, sound approaches the ear by vibrations in the air (or any other elastic medium) and enters the outer ear, which consists of the visible part (called the auricle, or the pinna) and the ear canal. The auricle is a thin plate of elastic cartilage, covered with integument, and connected to the surrounding parts by ligaments and muscles; and to the beginning of the ear canal by fibrous tissue [Wikipedia citation – Outer ear]. The ear canal is a tube leading from the bottom of the auricle to the middle ear, separated from it by the eardrum (or tympanic membrane). The main purpose of the ear canal is to focus the sound energy gathered by the auricle on the eardrum. It also amplifies frequencies between 3 kHz and 12 kHz.

Being gathered on the eardrum, the mechanical vibrations propagate through the middle ear. Three bones (called the ossicles) are located inside of it. The malleus (also called the hammer) is connected to the eardrum and transfers the vibrations from it to the incus (the anvil). These vibrations are quite chaotic, but the malleus is connected to the eardrum in a linear manner, also helping the ear to respond more linearly and smoothly. The incus, in turn, connects to the stapes (the stirrup). The footplate of the stapes introduces pressure waves in the inner ear, which starts with the oval window of the cochlea. The structures of the middle ear can be seen on Figure 3.1a

It may sound redundant to have additional structures in the ear which propagate the vibrations even further, when they could travel just one centimeter more in a way like before, in the ear canal, but in reality, the pressure of these mechanical vibrations is too small to cause the waves of the same velocity in the cochlear fluids. The ossicles help to amplify the pressure of these vibrations. They are positioned to form a lever, and, because the oval window is about 14 times smaller than the eardrum, the pressure gain becomes quite significant in the end –




(a) (b)

**Figure 3.1** **(a)** Anatomy of the human ear. The ossicles of the middle ear are shown in white. The inner ear is shown in purple. **(b)** Cross-section of the cochlea showing the organ of Corti and three chambers filled with cochlear fluids. Both pictures were taken from `https://commons.wikimedia.org/`

at least 18.1 times [Wikipedia citation – Middle ear].

To regulate the middle ear and protect it from damage due to very loud sounds, two muscles are located inside of it: the stapedius muscle and the tensor tympani muscle. These muscles are controlled by unconscious reflexes and hold the ossicles when the vibrations become too intense. To provide ventilation and drainage of the middle ear and to equalize pressures in this isolated environment, the middle ear is connected to the back of the throat by the eustachian tube [2].

## 3.2 Inner Ear

The inner ear starts with the above-mentioned oval window, which is connected to the stapes of the middle ear. The oval window is a part of the cochlea — a structure of the inner ear dedicated to hearing. Along with the cochlea, the inner ear also contains the vestibular system, which is responsible for the sense of balance and spatial orientation and uses the same kinds of fluids and cells as the cochlea does. The vestibular system will not be covered in this thesis, but the fluids and cells will be described in more detail later in the section.

The cochlea itself is a spiral-shaped cavity made of bony tissue, which makes about 2.75 turns around its axis and is about 3 cm long [Wikipedia citation - Cochlea]. The core component of it is the basilar membrane, which runs along almost its entire length and separates two of the three chambers of the cochlea filled with different fluids: the tympanic duct filled with perilymph (scala tympani), and the cochlear duct filled with endolymph (scala media). The third chamber, the vestibular duct (scala vestibuli), is separated from the cochlear duct by the Reissner's membrane and is filled with perilymph (Figure 3.1b). When the footplate of the stapes of the middle ear introduces movements to the cochlear fluids, the basilar membrane is affected too, and the endolymph in the cochlear duct moves along.

The most interesting property of the basilar membrane is that its stiffness and width is different throughout its length – the membrane is narrow and stiff at the basal end of the cochlea, and wide and floppy at the apical end. And here sound waves have two possible routes to take while propagating through the basilar membrane: a shorter path, which includes going through the

stiffer parts of it, or a longer path, which means travelling along the membrane until it becomes easier to pass through, but pushing more fluid on the way. In fact, high-frequency waves tend to choose the shorter path, and low-frequency waves – the longer one.

Thus, the basilar membrane moves in different places depending on the frequencies of the vibrations. The organ of Corti, which sits on top of it and runs along its entire length, contains displacement cells able to respond to movements of the fluid nearby and send electrical impulses when this happens. Such cells are packed with a bunch of stereocilia (hair) that stick out of its top, and thus are called hair cells. These cells can be of two types: inner hair cells that are located closer to the center of the cochlea, and outer hair cells that sit closer to its outer side. Inner hair cells are less numerous than outer hair cells and form a single row along the organ of Corti, while outer hair cells usually form three rows [2].

Now, it is important to mention that the endolymph in the cochlear duct contains high amounts of positively charged ions (primarily potassium and calcium). When it moves in response to the sound pressure, the stereocilia of the inner hair cells are deflected, and tiny ion channels open in them. This allows the charged ions from the endolymph to enter the stereocilia. The cell becomes depolarized, and a receptor potential is produced. This results in releasing the neurotransmitters at the basal end of the cell and then triggering action potentials in the nerve nearby. In this way, inner hair cells detect movements around them and convert mechanical sound waves to electrical nerve signals.

Outer hair cells, in turn, serve as amplifiers of the quiet sounds. Their receptor potentials are converted to cell body movements, thus increasing the sound pressure [4].

## 3.3 Auditory Scene Analysis

Chapter 4

# Mathematical Background

# Chapter 5

# Computational ASA

Now, having described all the underlying concepts from different fields of science in previous chapters, it is time to finally focus on computational auditory scene analysis. CASA is said to be a field of study that groups practical, programmable solutions for auditory scene analysis problems, and thus can introduce new discoveries and insights to it. CASA systems are used primarily for source separation, meaning that they are machine listening systems that aim to separate sounds from different sources in mixtures. However, they are not the same as systems for blind signal separation – the core difference is that CASA systems try to mimic (at least to some extent) the mechanisms inside the human ear, which were described in chapter 3. In this chapter, main principles of CASA systems will be described, along with a typical structure, desired outputs and applications. In the second part, major works that use computational auditory scene analysis for source separation will be reviewed and compared.

## 5.1 Typical Structure of a CASA System

# Chapter 6

# Implementation

# Chapter 7

# Experiments

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