A METAPHORIC SONIFICATION METHOD - TOWARDS THE ACOUSTIC STANDARD MODEL OF PARTICLE PHYSICS

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ABSTRACT

The sound of a sonification has, like any sound, a metaphoric content. Ideally, the sound is designed in a way that it fits the metaphors of the final users. This paper suggests a metaphoric sonification method in order to explore the most intuitive mapping choices with the right polarities. The method is based on recorded interviews, asking experts in a field what they expect data properties to sound like. Language metaphors and sounds of the recordings are then interpreted by the sonification designer. The method has been used for developing an 'Acoustic Standard Model of particle physics' with physicists at CERN.

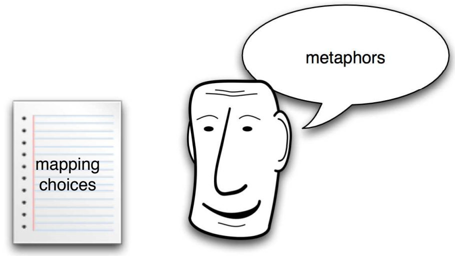

Figure 1: Metaphor sonification method. A questionnaire on sound metaphors and possible mapping choices.

1. MOTIVATION

Conceptual metaphors have been discussed, e.g. by G. Lakoff and M. Johnson [1]. Metaphors help us understanding an idea of a target domain by citing another one in a source domain. Even more fundamental, they shape our perception of reality. Also science builds on existing experiences: *"So-called purely intellectual concepts, e.g., the concepts in a scientific theory, are often – perhaps always – based on metaphors that have a physical and/or cultural basis. The high in 'high-energy particles' is based on* more is up. *[...] The intuitive appeal of a scientific theory has to do with how well its metaphors fit one's experience."* [1, p. 19]

For a *good* sonification design, it would thus be enough to know about the underlying metaphors of a scientific theory *and* the metaphors for sound of these basic experiences. By mapping, e.g., higher energies to what people in our culture perceive as *higher* in sound, a completely intuitive sonification could be created. B. Walker and G. Kramer [2] questioned already in 1995 if there is something like best auditory mappings for certain data properties and what they could be. They tested different mappings which they had assessed as *good* or *bad*, and were surprised by the actual outcome of the test, as the 'bad' mappings actually led to best results. The same authors point out that *"interface designers have usually implemented what sounds 'good' to them"* and conclude that testing with the final users is crucial. An effective mapping cannot be predicted a priori and also the polarity of mapping has to be taken into account. The results are also interesting in the specific context of our data, as they found for instance *"that increasing mass is generally best represented by decreasing pitch"*.

B. Walker conducted several studies in this direction [3, 4]. He implemented magnitude estimations between sound attributes and conceptual data dimensions. Magnitude estimation is a standard psycho-acoustical procedure for studying the dependancy of an acoustic variable on its perceptual correlate (e.g., frequency and pitch). Walker extended the method to conceptual data variables. For data-to-display pairs he found positive or negative polarities (the increase in a data dimension is reflected by the increase or decrease of the sound attribute), and scaling functions, giving also the slope of the dependency. In extensive experiments he showed that polarity and scaling functions matter for the quality of AD, and a priori predictions about the best choice are often difficult but can be determined empirically. For some mappings, the analysis showed unanimous polarities, as, e.g., for velocity to frequency. For most mappings, the positive polarity was dominant. While these results are highly valuable for sonification design, a complete analysis of the sound metaphors of any scientific theory is beyond the scope of creating an AD.

S. Barrass argues, that sonifications should be done in the 'world of sound' that the end-users know. In a physics' related context, e.g., the sound of a Geiger counter is one that can easily be understood, even if the data has nothing to do with radiation at all. *"The Geiger-counter schema also seemed to reduce the amount of time it took naïve users to learn to manipulate the [...] data, and provided a context for interpreting the sounds in terms of the geological application domain."* [5, p. 405] Also in the experiments cited above, different listener groups (e.g., blind and sighted people) chose different polarities as best data display. Walker concludes that *"sonification must match listener expectance about representing data with sound"* and that it *"is also important to consider the perceptual reactions from a more diverse group of listeners"* [4]. While the latter argument meant mainly individuals differing in listening expertise, we argue that also differences in the conceptual understanding of data dimensions play a role. Energy in the context of macroscopic objects might mean something completely different for engineers than in the microscopic view for particle physicists. In accordance to Walker, we assume that general metaphors that are valid in any context can never be achieved. There will not be a general table that a sound designer can simply read-out for any sonification problem. *"As with any performance data that are used to drive interface guidelines, care must always be taken to avoid the treating the numbers as components of a design recipe." [4, p. 596]*

Motivated by these assumptions, we developed a metaphoric sonification method, *metaphor*, Fig. 1. The basic idea is to question scientists in the field about the sounds or metaphors they use or what they expect special data properties to sound like. The method is a sensible starting point for sonification design, that allows informed parameter mapping choices for the designer. It can also be used for event-based methods as earcons or even for model-based sonification, where at least parameter tuning can be adjusted to fit the sound results to the intuition of the domain scientists. The method does not deliver a ready-made sonification design, but rather leaves creative space for the specialist who –by questioning the domain experts– gains insight into their possible 'world of sound'.

An existing approach to support the sonification design process is EarBenders, a database of stories on everyday listening experiences by S. Barrass [6]. He suggested this method in analogy to classical case-based design from human computer interaction, because the sonification community still lacks a considerable amount of case studies of ADs. The database can be accessed, when a new sonification design is demanded for a field, where the designer has no previous experience. One method of searching the database is a metaphorical one, as also Barrass argues that a *"metaphoric design can help when sounds are not a natural part of the design scenario, which is often the case in computer-based applications."* [6, p.51] But even with a large data base, a search for a new sonification problem often does not deliver exact matches.

There have many been different approaches to design guidelines in AD. For an overview, see [7]. Three conceptually different approaches shall be mentioned: the Task and Data analysis by Barrass [6], realized as a systematic questionnaire; the sonification design space map (SDSM) by de Campo [8], a map of quantitative data characteristics; and *paco* (pattern design in the context space), an iteratively evolving data base of design patterns [7].

The power of metaphors

A comment should be given on the human nature of sensorial metaphors. Mappings of conceptual data variables and auditory percepts are rarely homogeneous, i.e. judged similarly by different people, which may partly be a result to learning. But, it may also be intuitive in the sense that cross-modal metaphors are found in common language (e.g., a *tone* color). Martino and Marks [9] suggest this as a form of weak synesthesia as compared to strong synesthesia, where associations between an inducer in one modality cause induced percepts in another (e.g., seeing absolute colors when hearing corresponding tones). While correspondences in strong synestehsia are systematic and absolute, in weak synesthesia they are defined by context. The authors suggest a *'semantic-coding hypothesis'*: high-level sensory mechanisms are involved, which are developed from experience with percepts and language. Thus also language can cause percepts, and these are rather homogeneous within a group of people of the same cultural background.

2. A METAPHORICAL SONIFICATION METHOD

Our metaphoric guideline on sonification design is a similar approach as EarBenders, but for the case that no a priori sound examples exist. It allows the sonification designer to gain insights into the field from a meta-level point of view. The method is based on asking potential sonification users about which sounds they would expect or associate to the data and task. Different kinds of metaphors in the answers are then re-interpreted to the sound domain. The procedure can be generalized as M–ET–APH–OR:

Material: Become acquainted with the data. Define which features should be covered by the sonification. A TaDa (see [6]) may help in this task. Set-up a questionnaire, which may give you cues for the most important metaphors of the domain science. It should have a free, associative part, but also suggest mapping choices including the polarity. Define number and (the professional/ personal) background of the interviewees.

Enregister Talks: Interview domain scientists face-to-face and record the interviews.

Analyse PHrasing: Take notes on the questionnaire, extract and describe the sounds of the recordings. For instance, intra-personal fits or misfits between language metaphors and the produced sounds can be interesting. Collect the sonification ideas that have come up during the interviews. If there is enough data material, do some statistical analysis. Find common (interpersonal) metaphors. List also differing metaphors or cases where, e.g., the polarity of the mapping seems unclear.

Operate with Results: Based on the results of the questionnaire, decide on the best mapping choice and implement it.

The main finding of this procedure is knowledge about the specific metaphors and associations of scientists (or others) in their specific field. As a side effect, ideas for the basic sonification design can come up during the interviews – more, than a single sonification designer would have thought of. Also, if a domain scientist contributes to a sonification in this way, s/he spent already time with it and will be curious about the outcome. Thus the sonifications may be more wide-spread.

The recording of the questionnaire is important, as it is hard to speak about sounds, especially for people who have never done so before. Firstly, the recording allows the interviewees to *make* sounds rather than describing them. Secondly, misunderstandings can be avoided, especially when the interviewee and/or the sonification expert are not native speakers of the same language. It has to be taken into account that most test persons can think of more sounds than they can actually produce. The personal interview is very important, because it helps questioning the outcome of the sounds and interpret the metaphors behind. Finally, the recordings of the discussions can re-assure the sonification designer.

A disadvantage of the *metaphor* procedure is the additional effort. Also for a sonification design in a predominantly exploratory focus, the metaphors collected in the interviews do not help much, as new, unknown data features are searched for. But for any sonification with at least some known structures involved, this method helps for a good mapping choice and more acceptance in the domain community.

In developing the method, a study was conducted following the *metaphor* concept defined above. It is discussed in Sec. 3.

3. TOWARDS AN INTUITIVE PARTICLE DISPLAY

In particle collision experiments, e.g. at CERN, the European Organization for Nuclear Research, different kinds of particles are measured. The most common visual display shows colored tracks of particles that have been produced by a collision, sometimes as a movie. In a short term project in autumn 2009, I conducted a questionnaire on data from CERN, that supported the design decisions for an 'acoustic standard model' of particle physics. The description follows the *metaphor* procedure described above, even if the experiences from the survey were used to create the method.

3.1. Material

The Standard Model of particle physics describes a framework of three of the four known interaction types and the elementary particles that interact with each other. All visible matter in the universe is constituted by these particles. It is not within the scope of this paper to give a complete overview over the properties of these particles, but a schematic plot is shown in Fig. 5. There are 6 quarks and 6 leptons both for matter and (antiquarks and antileptons) for antimatter. The stable parts of everyday matter is built up by the *up* and *down* quark (constituting the proton and neutron) and the electron and electron-neutrino. Quarks have a so-called color property, and cannot be observed freely: only color neutral objects, as baryons (a blue, a red plus a green quark) or mesons (color plus anti-color, in this example blue and yellow) are observed. Baryons and mesons are both hadrons, as opposed to leptons like the electron and bosonic force carriers like the Higgs-boson (the Higgs has not been observed and is thus a theoretical particle). There are hundreds of particles which are constituted by different quarks, therefore often referred to as a 'particle zoo'.

We elaborated a questionnaire on particles, containing a short introduction and 3 other parts. The participants were chosen from employees at CERN who have studied physics.

After a short introduction, free associations for eight different particles were being asked for: p: proton, p-: antiproton, e: electron, e+: positron, μ: muon, π: pion, $\kappa^{\pm}$: kaon, h: Higgs boson. The particles are the most common (in our data from CERN), and cover the most important features, like mass, matter (vs. antimatter), charge, and quark content (for hadrons). We included the Higgs' boson as the only imaginary particle, because it was a 'hot topic' at the time at CERN and in the media. This part of the questionnaire was recorded.

The second part of the questionnaire was only shown, after the free, associative part has been completed. A table of sound properties with pairs of extreme positions was given (see Fig. 2). We tried to phrase these properties in a general, rather musical wording, avoiding technical terms. The list was open ended and could be complemented by the interviewees having any other ideas.

Then, different particle properties were listed: mass (*heavy vs. light*), matter (*matter vs. anti-matter*), charge (*positively/ negatively charged vs. neutral*), quark content (*up, down, charm, strange, top, bottom*), particle type (*mesonic/*

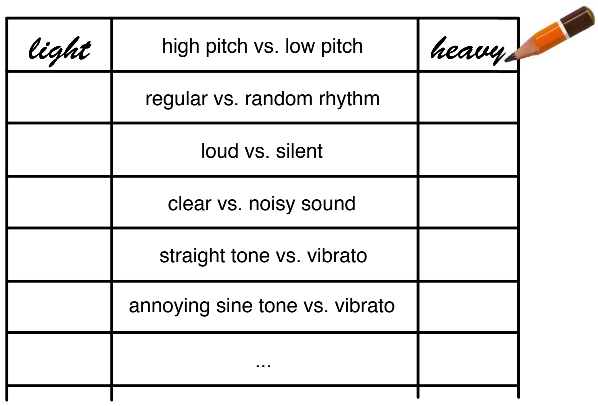

Figure 2: CERN questionnaire - I: Schematic plot of the sound properties' table with an exemplary mapping choice.

baryonic/ leptonic), and excitation, again in an open ended list. They could be chosen and filled into the left or right hand side of the sound properties' table, see Fig. 2. Properties not associated with any sounds were left out.

Finally, personal information including total years working in the field (including studying), specifying the field, years working at CERN, gender, and whether the persons ranked themselves as (partly) musicians, music lovers, or none of these, was collected.

3.2. Enregister talks

All interviews were conducted personally by mysef and had no time limit. In the open part, no additional information was given than a short introduction to the project. If the test persons were comfortable with this, they were asked to mimic sounds they imagined, or else to speak about their associations.

24 people ranging from a diploma student to a Nobel prize laureate have been interviewed (according to [4, p.596], this number is appropriate for such an experiment). Three participants were excluded from the analysis, as they had not studied physics which I only found out during the interview. One person did not want to be recorded or complete the questionnaire, but made some general remarks. One interviewee completed only the first, associative part, but not the fill-out part. Thus, 19 questionnaires were included in the analysis of which two were completed by females and the remaining 17 by males. Five interviewees ranked themselves as *(partly) musicians* and three as *none*, the rest as *music lovers*. The lengths of the interviews averaged around 15 minutes.

Reactions of the interviewees were very diverse. The task of thinking about the sound of particles, or even mimicking them, was too demanding for some: *"I am shocked"* clearly reflects that. Many people reacted in a way, that they were not the right person to ask: *"You know better than we do what to choose"*, or *"What you need is a synesthete!"*. Many participants established a relationship to their actual field of work. For instance, experimental detector physicists would say, *"I am thinking of layers because I am working with detectors and their layers"*. One even extended the notion of a particle detector to the human hear, and suggested to use very high sounds for particles which are hard to detect: *"I am already hard of hearing with high pitched tones"*. Those, who did try to mimic the sounds they thought of, experienced problems with the task. *"I hear my sound and I think - 'Ahh, that's not exactly what I meant'. I cannot produce all the sounds that I imagine."* One participant tried his sounds out several times in order to improve fitting his actual voicing to his imagination.

Nevertheless, 12 people did produce sounds and three participants even suggested specific sounds for all eight particles on the list. The recordings of the free questionnaire part for all particles are available at http://qcd-audio.at/tpc/quest.

Resulting mapping choices of the fill-out part are shown in Tab. 1.

3.3. Analyse Phrasing

For the analysis of the metaphoric sounds, the particle sounds were cut from the recordings and normalized. Also the spoken descriptions were collected, and general ideas for the sonification design extracted. The approaches in the recordings can be summarized as follows:

- Most people started systematizing even in the free, associative part – they are trained physicists. A clear majority suggested to map mass to pitch as a very first association.
- Phonetic or spearcon approaches following the particles' names were often applied. For instance the Higgs' sound was associated with a *"higgs"* or just *"igs"*, or proton became an *"ooo"* and the pion an *"iii"*.
- Many comparisons to the measurement were drawn. E.g., heavy particles crush *loudly*, or particles behave differently in various layers of the detector.
- Some suggestions were very concrete. (The examples cited here were taken into account in the display.)
  - Tone patterns, like J. S. Bach did with his famous b-a-c-h fugue, would allow recognizing particles. Simple particles, like protons, can become something like a bass line.
  - Each quark flavour can have a certain pitch assigned, meaning that hadrons are played as chords (thus baryons would sound as triads, for instance).

Pitch:	mass (18/18), favorit: mass
Amplitude:	mass (7/14), charge (4/14), matter (2/14), favorit: charge
	(mass will be used for pitch, and does not need to be mapped twice, as pitch is a very strong mapping factor; charge was cited second most often)
Rhythm:	lep/ had (3/12), mass(2/12), matter (2/12), individual suggestions (3/12), no clear favorite
	in general, rhythm is more associated with the experiment, measurement or data
Noise component:	lep/ mes/ bar (7/14), matter(3/14), quark content (2/14), favorit: lep/ mes/ bar
	(but no clear mapping choice due to inconsistent polarities)
Vibrato:	exc. (6/14), lep/ mes/ bar (4/14), matter (3/14), charge (2/14), favorit: excitation
	(here the problem was different notions of excitation; we referred to ground state and excited states, but this is not reflected in measurements, and was thus often interpreted differently. Still, vibrato would be the favorite mapping for excitation.)
Timbre:	matter (2/8), exc. (2/8), lep/ mes/ bar (2/8), no clear favorite:
	and only few total number of suggestions (possibly, this is concept is too complex)

Table 1: Mapping choices of the particle properties resulting from the MSM. The number of mentions vs. the whole number of all answers for this property is shown in brackets. Abbr.: lep=leptonic, had=hadroniv, mes=mesonic, bar=baryonic, exc=excitation.

- Matter is a normal sound and anti-matter its reversed playback.
- Particles sound like *cars passing by*, with their passing time and pitch variation depending on their speed.

Some statistical analysis was done, but as only 19 people were taken into account, no significant results have been found regarding different backgrounds. Fig. 3 shows how often particles were mimicked with sound or described (in words) in the associative part of the questionnaire. The Higgs' particle was treated most often, possibly because it is talked about a lot. The Higgs' sounds were often meant to be funny, e.g., a *"tadaa"*, like the theme of a feast, or a *"ka-boum"* for some ground breaking discovery. Neglecting the Higgs', the figure shows that well-known particles as electron and proton are cited most often. There are much fewer associations for rare particles.

Some particle properties were used much more often for mapping suggestions. Many test persons linked mass, the general particle type or matter (vs. anti-matter) to sound properties. Mass, for instance, has a macroscopic meaning that can easily be associated with sounds. The particle type (as hadronic or leptonic) is more abstract. For anti-matter, many explanatory metaphors exist - e.g., an anti-particle was described as its particle *"seen in a mirror"*. The quark content, at the end of the table, is an abstract property and was only cited five times summing all mentions of the 19 test persons together.

The most obvious mapping choice was pitch with mass, heavy mass meaning low pitch. *All* answers in the table were given accordingly (only the direction of the mapping was *once* given contrariwise, high mass being mapped to high pitch). These results are in line with experiments of Walker [4], where also a few (2 out of 19) participants chose

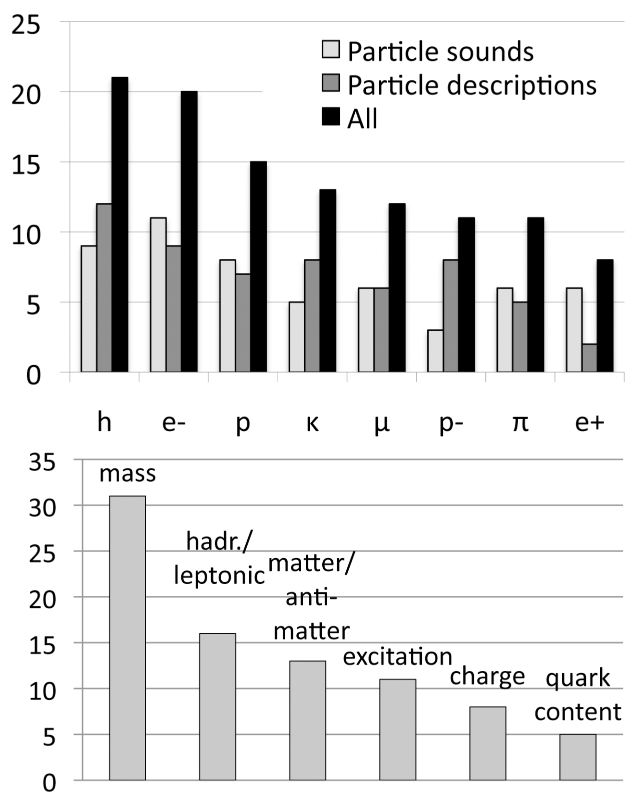

Figure 3: Quantitative results for the CERN questionnaire: *Upper figure:* Overall number of particle descriptions and sound associations, sorted by their sum.
Lower figure: Number of entries of the particle property into the sound properties' table.

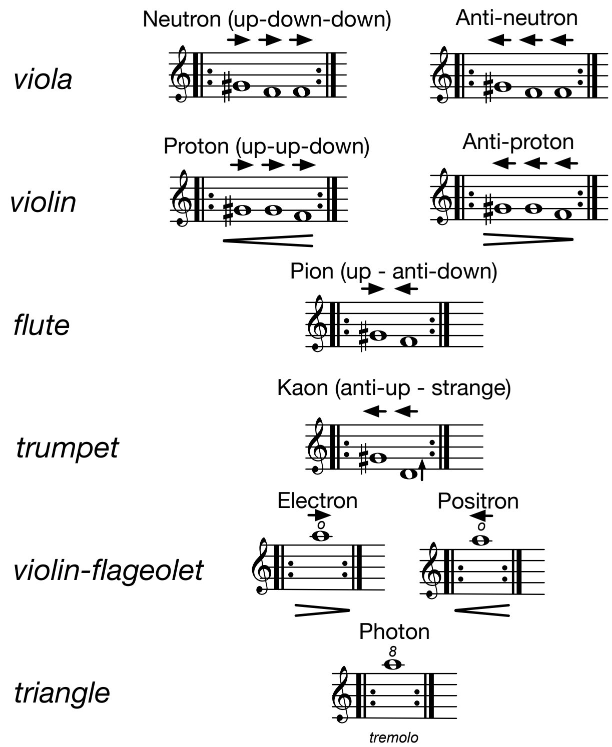

Figure 4: Example for the acoustical standard model. The forward and backward arrow denote the forward or backward playback time for each elementary sound.

opposing polarity for mass to frequency. In general, increasing sound frequency corresponds to decreasing mass.

Results of the sound property table are shown in Tab. 1. The most prominent choices were used for basic mapping decisions: Mass, as a central particle feature, clearly was linked to *pitch*, which is a salient auditory percept. Charge was suggested for *amplitude* second most often after pitch. In general, *rhythm* is more associated with the experiment, measurement or data. There was no clear mapping choice for *noise*, due to inconsistent polarities. Vibrato would be the favorite mapping for excitation.[1] *Timbre* had only few total number of suggestions, possibly because this is concept is too complex.

3.4. Operate with Results

In general, each particle shall be displayed as a recognizable sound of varying length, which is transformed under the dynamics dictated by an experiment. With all knowledge from above, we worked out the following sonification:

[1]Though, it should be mentioned that there were ambiguities with the term 'excitation', which is referred to excited particle states vs. the ground state, as this cannot be seen directly in experiments.

Mass is mapped to pitch, and every elementary particle (quarks/ leptons/ bosons) has an assigned pitch. First generation quarks (up and down) form a small, regular interval (a third). The strange quark is a *strange* mistuned fourth, and the charm is the *charming* octave, all in relation to the lightest and highest pitched up quark. Bottom and top quark follow each an octave lower. Perceptual grouping between different quark generations is difficult, but such composite particles are rarer anyway.

The leptons are separated in higher registers, and have a *light*, e.g. a flageolet sound. The according neutrinos follow as clear sine tones an octave above the leptons. The pitches vary slightly for every observable around these frequencies. In Fig. 4, some examples are shown.

Every sound has a clear attack and decay, and for antimatter, the sound is just reversed.

Hadrons are composites of 2 or 3 quarks - the according pitches are played successively as a tonal pattern, always starting at the highest pitch. Also the tone lengths of the quark sounds vary with mass, resulting in a polyrhythmic structure.

Charge is given by a crescendo (for positive) and a decrescendo (for negative charge) on the whole structure (the tonal pattern for hadrons or single sounds for the other particle types). A neutral particle is steady in amplitude.

Each observable (a hadron or a lepton) is played by one musical instrument. This assures the perceptual grouping of the single quark sounds to one coherent particle and allows a certain characteristic by its timbre. Surely, more hadrons exist, than perceptually distinguishable instrumental timbres are available, but they rarely all appear in a measurement together. A violin sound can be used for the often occurring proton, as it is the dominant instrument of the orchestra. A viola sound is chosen been as the more 'neutral' instrument in comparison to the proton-violin, representing the neutron.

The experiment dynamics can be implemented as spatialization and/or the Doppler effect, using the *'car-passing-by'* association mentioned above. With this basic scheme, also other particle displays are possible: e.g., the sonification of 'static' Feynman graphs.[2]

4. DISCUSSION

The *metaphor* procedure proved to be helpful for our purpose, and the resulting sonification design is a coherent and possibly intuitive 'Acoustic Standard Model of particle physics'. Though a free, associative approach is rather demanding for the test persons, they surprised me with many interesting sonification ideas and with the sounds they were ready to make.

[2]Feynman graphs are a complete schematic representation of equations describing for instance particle decays.

Some outcomes may not be surprising to those who have been studying intuitive mappings before. As cited above from [10], high mass is normally linked to low pitch, which also makes perfect sense from a macroscopic experience point of view. Still, we found it interesting to ask physicists about microcosmic structures, where high mass equals high energy, and could in principle be mapped to pitch with a different polarity (high energy to high pitch). The analyses showed, that the high mass - low pitch metaphor is so strong, that it also holds for microcosm and is even mentioned as a first association in open questions.

There is a trade-off between *open* and *concise* questions. While the sonification expert should not lay too much of her/his own ideas into the questions, this might also lead to some misunderstandings. Misinterpretations occurred probably with the sound parameters, as they were explained in 'non-technical' terms. This could be – and should be – solved by *playing* actual sound examples to the participants.

Some conclusions can be drawn on the particle data set and the participants. 'Everyday' properties, like mass, are cited much more often than abstract ones, like quantum numbers. Imagination is limited when the participants are only used to mathematical treatment, or, the metaphorical shift from mathematics to a perceptual quality is too demanding for a simple questionnaire. Analysis showed also, that the concepts of particles become clearer, the longer people work in the field. This can be a benefit as strong metaphors emerge from professional experience, but also a drawback, as there is a lack of flexibility with new modalities, as sound.

The method in general helps with basic design decisions, but also restricts it. While sonification of complex data is already very demanding, another condition has to be taken into account. The *metaphor* method is indeed easily applicable for parameter mapping. However, for model-based sonification, the possibilities for metaphoric sound design are rather limited. Metaphors can still be implemented in the model design (rather than the sound design).

An open question not directly covered by the proposed method is the evaluation of the sonification. This has to be achieved by other methods.

5. CONCLUSION

We described the metaphoric sonification method as a procedure to explore metaphors in a scientific field and use them for a sonification design. We questioned and analyzed 19 physicists at CERN about their expectations, and created an auditory particle display based on the result.

Listening examples

The recordings of the free questionnaire part for all particles are available at http://qcd-audio.at/tpc/quest.

Acknowledgments

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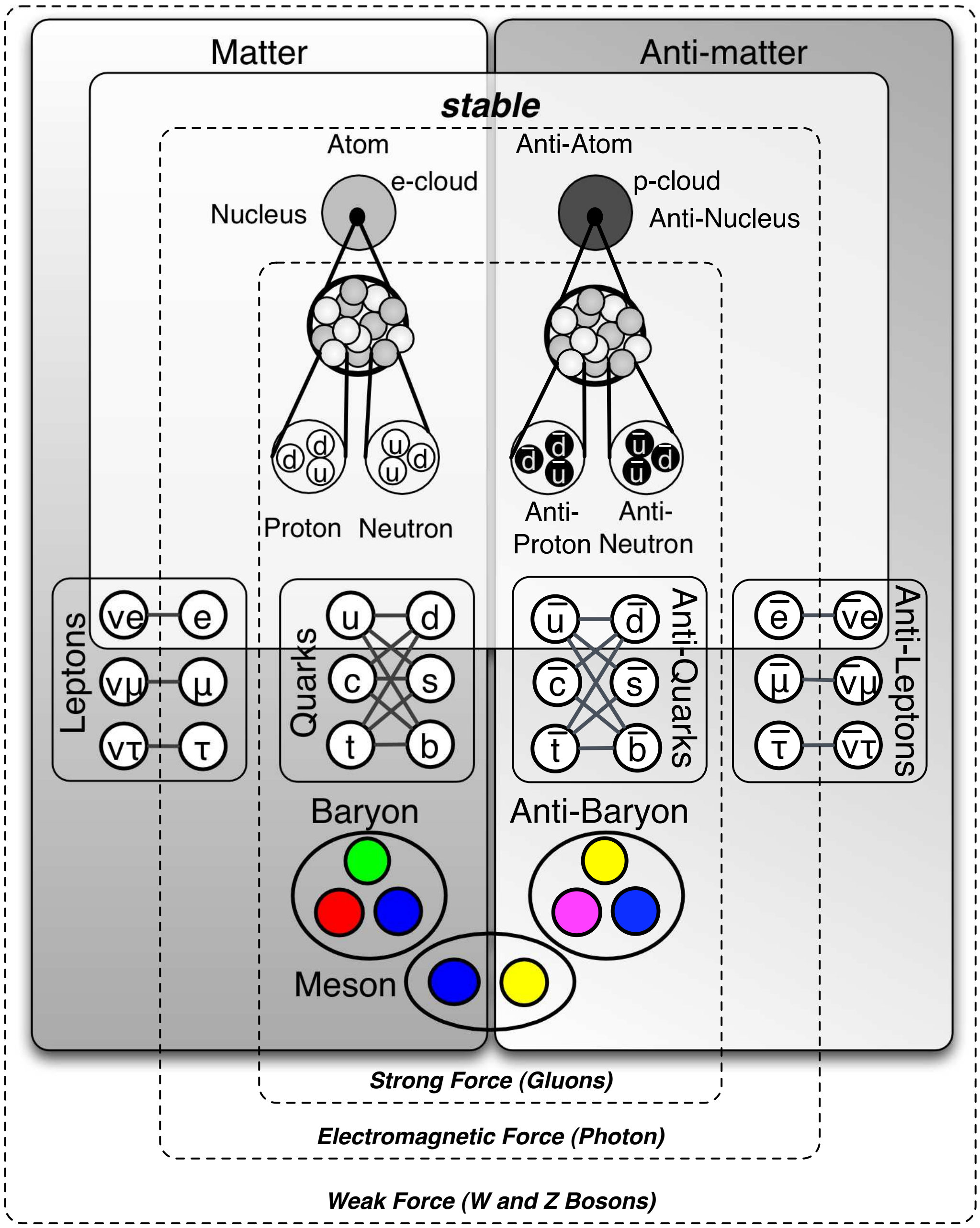

Figure 5: *Overview of the elementary particles in the Standard Model. The anti-particles are not shown but are completely analog to the matter-side. The following abbreviations are used: Leptons: ν_e - electron neutrino, ν_μ - muon neutrino, ν_τ - taon neutrino, e - electron, μ - muon, τ - taon; quarks: u - up, d - down, c - charm, s - strange, t - top, b - bottom. They are sorted in 3 generations with possible interactions indicated by lines between them.*