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ORIGINAL ARTICLES

Sounding Out Science: the *Sonaphor* and Electronic Sound Design as a Learning Tool in Secondary Science

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Abstract
The divergent use of digital technologies provides an important opportunity for students to develop critical and postdigital approaches to learning. Despite the rising accessibility of music technology, creatively composed sound is a relatively underexplored educational tool compared to the musical elements of melody, rhythm, and lyrics. Sound's ability to transfer spatial and temporal information renders it a transformative tool for teaching and learning. Embracing an interdisciplinary approach, our research explores the possibility of supplementing secondary science education with a sound-based learning tool which creatively interprets scientific concepts to increase comprehension and engagement. Building on the existing ways in which science is communicated through music and sound, we have developed the *Sonaphor* (abbreviated from 'sonic metaphor'). This article will outline the capacity for experimental electronic sound design to increase engagement in contexts ranging from classrooms through to informal learning environments. We see potential for the *Sonaphor* as a learning tool that reignites wonder and curiosity in science; it combines learning and creativity in sound design and science, allowing learners to interact with, and create their own *Sonaphors*. Through exemplar *Sonaphors*, we highlight a proposed structure and discuss the importance of harmonious script, dialogue, and sound design. The flexibility of the digital medium and increasing ubiquity of sound recording and editing software presents an opportunity for *Sonaphors* to become 'living' digital objects that could be adapted by different narrators, sound designers, and artists for different cultures, languages, syllabi, and purposes that build inclusivity in science education and communication.

Keywords Science education · Arts-based pedagogy · Semiotics · Sound design · *Sonaphor* · Podcast

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Introduction

Sound has the ability to communicate information in four dimensions. The physical impact of sound waves against the eardrum relays both spatial and temporal data to the listener, enabling them to determine a sound's original location and its movement over time, thus locating itself in relation to the listener. Non-musical sound is able to tell us much more than just the content of the sound signal itself (Gershon 2011). Using spectromorphological[1] variables such as volume, length, texture, timbre, rhythm, structure, pitch, and harmony, sound has the ability to create an imaginary space *around* a listener–the 'composed space' (Smalley 1997: 22). This ability renders non-musical sound a potentially transformative tool for teaching and learning. In this paper, we explore the potential of non-musical sound to guide listeners in constructing dynamic models of scientific concepts in their mind's eye.

Our interest in the use of sound to communicate scientific concepts is inspired by evocative approaches of composers and artists working in science communication, sound design, and radio (with WNYC Studios' RadioLab[2] providing particular inspiration). To date, much of the work uniting music and science has focused on improving public engagement in science or providing an up-beat and enjoyable way to revise content (Governor et al. 2013). Despite the clear benefits these creative products can impart, including enticing people to *continue* their scientific education, there exists rich potential to *ignite* the initial learning process by creatively exploring basic building blocks of scientific understanding.

Science is an inherently visual field of knowledge where the ability to imagine a three-dimensional structure with sometimes innumerable moving pieces can be essential for understanding, innovation, and communication (Gilbert 2008; Jones and Kelly 2015; Kozma and Russell 2005; Lemke 2005; Luisi and Thomas 1990; Prain and Tytler 2013; Tuckey and Selvaratnam 1993). An example of a foundational chemistry concept familiar to many school-leavers is the structure of the atom. Found at the beginning of most chemistry textbooks (Cooper and Stowe 2018), visual depictions of the atom generally include protons and neutrons as coloured balls, packed tightly into the atom's core (the nucleus), with smaller coloured balls of electrons positioned on circular or elliptical loops around the nucleus, coupled with symbolic depictions of their movement around the atom. The image conjured in the reader's mind (or shown in Fig. 1) represents a common form of communication in chemistry: static diagrams accompanied by gestures or symbols denoting movement (Danielsson 2016; Lemke 2005). Despite their repeated use, these diagrams have some inherent limits in educational effectiveness due to their

[1] Spectromorphology is a term coined by the acousmatic composer Denis Smalley (1997). It refers to the changes in sound (variables such as volume, length, texture, timbre, rhythm, structure, pitch, and harmony) and how these can be shaped over time (Smalley 1997: 107). Smalley discusses this as a tool used by a composer to select sound materials and shape their behaviours, in order to create an impression of physical space from sound.

[2] Radiolab is a podcast which uses an investigative journalism style to explore diverse topics from different disciplines. The episodes are often teeming with field recordings and sound design. See https://radiolab.org/. Accessed 27 May 2022.

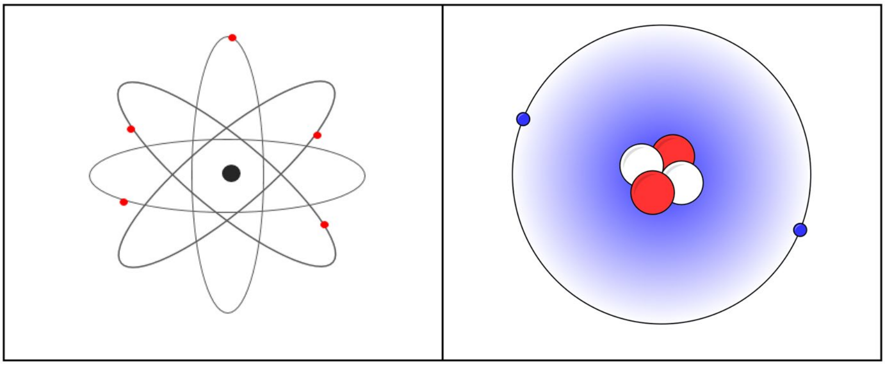

Fig. 1 Static depictions of the Rutherford (left) (Wikimedia 2021) (CC BY-SA 4.0) and Bohr (right) (Wikimedia 2019) (CC BY-SA 4.0) models of the atom which are commonly used for educational purposes (Justi and Gilbert 2000)

inability to communicate three-dimensional, movement and process-based information (Danielsson 2016; Gilbert 2005; Tasker and Dalton 2006).

Our team recognised the ability of non-musical sound to construct movement and space. In our use of sound as an educational tool, we aim specifically to exploit the intrinsic connections between the aural and the visual in order to guide the listener to create and annotate a four-dimensional mental image.

While sound can and certainly should be considered a unique modality of experience, our use of sound relies on phenomena referred to as 'imaginary projection and transference' (LaBelle 2010) and 'transmodal perception' (Smalley 2007) where senses such as sight, movement, and touch are activated by connecting sound events to previous experiences, thus conjuring an impression of real-life occurrences. Just as one might hear the word 'square' then see the shape in their mind's eye, one might hear a reedy, staccato bird call and form a mental image of a duck.[3] Further, effective sound design has the ability to immerse the audience so deeply in a narrative, such that their minds are able to be convinced of new connections between sights and sounds, and they can imagine that a seen object has new characteristics and behaviours (Murch 1994). It is therefore possible to take existing sounds and place them in new contexts where their previous anecdotal value is discarded, forcing the listener to create new fantastical associations and ideas.

Murch (1994) and Smalley (1997) both attest to the ability of composed spaces to combine realistic and imagined elements, providing a canvas on which the constraints that visual representations contend with, can be transcended. There is, therefore, a strong foundation to explore the use of creative and even unexpected sounds to engender a mental image which is individual to the listener, but can still vibrantly and accurately evoke an image of a scientifically acceptable concept.

[3] An example the reader may be familiar with from Prokofiev's *Peter and the Wolf* (1936).

Postdigital theory presents exciting possibilities for education, as it 'opens up new spaces to understand learning across wider perspectives' (Jandrić and Hayes 2020: 288). Common practice in educational settings tends towards societally driven, top-down implementation of technological tools that are expected to 'solve learning problems' in classrooms (Lowyck 2014; Jandrić and Hayes 2020). This is problematic when technologies are used non-critically, and replicate past analogue practice that do not reflect the leaps and bounds of the last few decades of pedagogical research (Lowyck 2014; Cormier et al. 2019; Savin-Baden and MacKenzie 2022). Postdigital theory 'offers the possibility to unlearn in order to relearn, together' Jandrić et al. (2019: 173), as it provides a 'starting point for applied research and the development of instructional principles and devices' (Lowyck 2014: 12). The education community must begin to work towards developing tools which allow for the navigation of a more symbiotic relationship with technology in classrooms that can 'enhance the development of the whole person (social, emotional, spiritual, moral, etc.)' (Fulgham et al. 2015: 44). Therefore, in our work, we make an attempt to develop a practical tool for use in the science classroom which has the potential to foster postdigital learners.

Aims of This Paper

This article will delve into the ways we can use sound to enhance the existing sensory landscape of science (particularly chemistry) education. Acknowledging the many meanings and applications of *sound* across multiple fields of knowledge, our research refers to the use of sound as a creative and designed element within the defined framework of a short podcast, redolent of sound design found in games, podcasts, or film. We add dialogue to direct the focus of the listener towards important aspects of the composed space and aid in their interpretation of the designed sound. In addition, just as the ambient and human-constructed sounds of an inhabited classroom can locate a student within the learning space (Gershon 2011), an ambient soundscape is used to help the listener feel immersed in the experience of listening to the *Sonaphor*. Together, the elements of designed sound and dialogue communicate conceptual, spatial and process elements of chemistry and nanoscience.

We use secondary chemistry education as the case study for what could be a wider education revolution that places designed sound, music, and rhythm as common features–rather than a novelty–in both formal and informal education spaces. In doing so we also propose ways to further expand the interdisciplinary nature of science and the diversity of those who contribute to and learn about science. To exemplify this process, let us revisit the example of atomic structure. By replacing a static visual with spoken word and introducing thoughtful use of sound in motion to illustrate a *mental* visual, rather than a literal one, we sought to create a tool that could contribute much of the information that learners cannot take from a visual diagram.

Existing Intersections Between Music, Melody, Sound, Science, and Education

Analysing the success of previous explorations of science, music, and sound in contemporary and popular culture allows us to position our project as part of a period of experimentation in science education and communication. Below, we discuss the many intersections of sound and science, including its existing manifestations within the science classroom. We then identify some particularly relevant examples communicating science through different aspects of the audio experience, namely lyrics, music, and sound design.

Sound Studies in Education

Sonic studies is a vast and inherently interdisciplinary field that examines the dearth of vocabulary and awareness around our lived auditory experiences (Oliveira 2018), and investigates the ways in which sound forms ‘systems of meaning’ (Gershon 2011: 68) in different societal environments.[4]

Within educational foundations, sonic studies highlights the role of intentional and incidental sound within the learning environment (Gershon 2011; Gershon and Appelbaum 2018). Gershon (2011) describes the value of sound as educator in the classroom, with the systematised sounds of the school (i.e. the lunch bell), the susurrations and murmurs of students and wider, ambient noise surrounding the learning space, all acting as grounding and contextualising elements which convey a sense of place and belonging.

Sonic studies provides a framework for research and analysis of the classroom ecology, but also an exciting opportunity for the development of new learning tools; for sound to take a central role in the learning process. Sound plays a different, yet critical educational role for young people *outside* the classroom, in styles and mediums (many technological) which are often seen as irrelevant to formal learning (Thibeault 2017). Sonic studies allows us to acknowledge that every environment is ‘deeply enmeshed with technological change’ (Thibeault 2017: 80) and to find a place for the rich, external sonic lives of students within the formal learning environment. We extend the role of sound from the ambient classroom to the curriculum, in styles and genres which reflect the extracurricular changes which shape our students’ lives outside of school but without ‘focusing on the gadgets’ (Thibeault 2017: 79) which enable them.

Communicating Science Through Lyrics

A common approach to incorporating music into scientific learning is to replace existing lyrics of popular songs with content-rich science lyrics (Baum 1995;

[4] The more musicological branch of sonic studies will be explored in the sub-heading *Preserving Soundscapes for Art, Science and Analysis.*

Baxter 2020; Blais 2017a, b; Last 2009; Pye 2004). These songs are effective in promoting interest, improving student understanding, and enhancing recall (Bellezza 1981; Crowther et al. 2016; Governor et al. 2013). They possess a unique ability to bridge the gap between artistic pursuits and scientific learning, making the content personally relevant to learners (Crowther et al. 2016; Gallagher et al. 2021) and diversifying the pedagogical toolbox of science educators (a necessity raised by Gallagher et al. 2021). The main function of these songs is to allow for *revision* and *consolidation* of scientific concepts that learners are already familiar with, or to ignite initial interest in a topic and prompt further exploration.

Tim Blais of A Cappella Science[5] creates engaging musical covers of popular songs, two being *Evo-Devo*[6] (2017) (covering Justin Bieber's *Despacito*[7] 2017) and *The Molecular Shape of You*[8] (2017) (covering Ed Sheeran's *Shape of You*[9] 2017). These 'a capella parodies' engage listeners in highly technical scientific concepts by weaving together rich harmonies and detailed, fast-moving lyrics, in what Blais describes as 'edutainment'.[10] Dr Raven Baxter, AKA Raven the Science Maven, continues this lyrical dexterity in her *Antibodyody Antibody Song*[11] (2020) (cover of Megan Thee Stallion's *Body*,[12] 2020), which contains high-level biochemical concepts designed to assist students' revision efforts.[13] Both Blais' and Baxter's content serve to reinforce and build on existing knowledge while continuing to engage learners.

Unlike the examples from Blais and Baxter, alt-rock band They Might Be Giants (TMBG) use original musical compositions to introduce basic scientific concepts to primary aged learners in their 2019 album, *Here Comes Science*.[14] Despite being reluctant to describe their work as educational, instead describing the tracks as 'purely creative exercises', the band chose to work with a scientist to ensure they 'got their facts right' (Thill 2009). Each melodic track focuses on a specific scientific topic; titles include *Meet the Elements*[15] (2009) and *Photosynthesis*[16] (2009). The interdisciplinary collaboration on this album demonstrates the utility of music in enhancing and accurately delivering the building blocks of science.

[5] See https://www.acapellascience.com/. Accessed 27 May 2022.
[6] See https://youtu.be/ydqReeTV_vk. Accessed 27 May 2022.
[7] See https://youtu.be/dr_GAJZviR0. Accessed 27 May 2022.
[8] See https://youtu.be/f8FAJXPBdOg. Accessed 27 May 2022.
[9] See https://youtu.be/JGwWNGJdvx8. Accessed 27 May 2022.
[10] See https://www.acapellascience.com/. Accessed 27 May 2022.
[11] See https://youtu.be/KBpQg6JMxSc. Accessed 27 May 2022.
[12] See https://youtu.be/7PBYGu4Az8s. Accessed 27 May 2022.
[13] See https://www.scimaven.com/. Accessed 27 May 2022.
[14] See https://www.theymightbegiants.com/here-comes-science. Accessed 27 May 2022.
[15] See https://youtu.be/KkTdhWbnRPk. Accessed 27 May 2022.
[16] See https://youtu.be/6LoU4kh3mVY. Accessed 27 May 2022.

Encoding Scientific Information in Music

While the examples above show how lyrically driven music can deliver value to scientific learning at different stages, some recent examples from the field of biology encode biological information into the music itself. Composers have converted data such as amino acid sequences of proteins (Takahashi and Miller 2007), epigenetic tags (Brocks 2015), and microbial ecological data (Larsen and Gilbert 2013) into music. All aim to remain true to the data while creating a musically engaging output–hence their primary focus could be considered as *motivating* the public to learn more about science rather than instructional.

Encoding Scientific Information in Sound

The above examples lead naturally to a broader discussion of the use of sound to communicate data ('sonification' or 'auditory display'). Sonification has been explored as a technique to communicate scientific processes and numerical data, due to its ability to present 'detailed and abstract information' (Yu and Brewster 2002: 63), and finds particular use as continuous sound which creates awareness of *changes* to data over time (Hermann et al. 2011; Langeveld et al. 2013). According to Hermann et al. (2011: 3), the human auditory system is unparalleled by technology in its ability to recognise and sort multiple levels of patterns and develop 'novel and helpful characterizations of the data' due to its 'complexity, power, and flexibility'. This is perhaps why sonification has been found to enhance the efficiency of human information processing when used in tandem with other sensory data in medical settings, aviation, engineering, and emergency services (Barrass and Kramer 1999). An inherently interdisciplinary technology, sonification requires input from multiple fields in order to optimise the delivery and comprehension of information (Hermann et al. 2011); it demands a level of creative interpretation and hence finds a natural home as the basis of many creative projects.

The use of sound to communicate information also facilitates the inclusion of science students and practitioners who are blind or have low vision. There has been much investigation into the benefits of non-visual modes of diagram representation, including both static and dynamic tactile representations (through methods such as braille and topographic models), multimodal representations combining haptic and sonic delivery, and solely sonic representations drawing on parameters such as pitch, speech, and sound design elements (called 'sound diagrams'), for example *earcons*[17] (Bennett 1999, 2002; Yu and Brewster 2002). Yu and Brewster (2002: 63) have demonstrated that the inclusion of sound information with tactile diagrams enhances their efficacy. Although powerful, these technologies are designed with the intent of depicting a concept which is inherently visual (Yu and Brewster 2002: 161) rather than re-imagining this information in a way optimised for sonic comprehension.

[17] *Earcons* are abstract sounds that symbolise actions or alerts and are learned by the user of a product (Langeveld et al. 2013).

Preserving Soundscapes for Art, Science, and Analysis

Sonic studies, in the purest sense, finds its origins in Schafer's concept of the 'soundscape' (Schafer 1977, 2006), a term used to describe the myriad ephemeral sonic environments of the past and present, natural, and anthropogenic. The word 'acoustemology' (Feld 1994) has since appeared to describe the study of 'acoustic knowing' (11), or how sound imparts layers of meaning to the listener.

Schafer's concept of the soundscape is the centre point of a movement to restore our modern existence to a more natural, less noise-polluted state (Kelman 2010). Acoustic ecology, or ecoacoustics, was a term coined by Schafer (2006: 11) to describe this concerted act of listening to the acoustic environments around us (Wrightson 2000; Schafer 1977), and even 'restoring the balance between living creatures and the natural environment' (Schafer 2006: 11). Now a growing international practice, it involves monitoring the environment for both healthful and 'destructive' sounds (Schafer 1994: 4)–a fantastic example being the Australian Frog ID project[18] (Weaver et al. 2020). Ecoacoustics can also provide rich information about the way different communities and cultures interact with their environments (e.g. Feld 1994). For composers however, the emotional and creative perception of these field recordings is a crucial element of the delivery (Barclay and Gifford 2018).

Creative manipulation of field recordings and immersive spatialisation can serve to promote awareness of the environmental soundscape and human impacts on it, thereby empowering the communities to care for their environments–one such example being Paine et al.'s Listen^n Project (2015). Through generation of an extensive field recording database of America's Southwestern deserts, the Listen^n Project prioritised involvement of local communities and gave them a sense of ownership over the initial capture and creative interpretation of sounds (Paine et al. 2015). More than an artefact of ecological science or ethnomusicology, ecoacoustics can be viewed as 'the middle ground between science, society and the arts' (Schafer 1994: 11), and sheds light on the importance of sound to the human experience (Epstein 2003; Feld 1994).

Combining Music, Sound, and Narration to Enhance Meaning

Radio plays, podcasts, and on rare occasion audiobooks harness the immersive capabilities of sound to enhance the delivery of the spoken word. A particularly successful example of the use of sound to enhance non-fiction narratives is WNYC Studios' RadioLab. Radiolab often uses non-diegetic music and sound when scientific phenomena or events are discussed, with sounds and ambiences directly illustrating what is being recounted by hosts or guests.

[18] See https://www.frogid.net.au/. Accessed 27 May 2022.

A striking example of this sonic enhancement occurs within the episode *Elements*[19] (2021). While hosts Abumrad and Krulwich and guest Derek Muller discuss the synthesis of chemical elements (within a star, then a supernova), Muller describes the process of 'taking atoms and smashing them together … combining them', and a highly evocative *whoosh* and *impact* gesture is overlaid on the soundscape (30:00). Later, these smashing, whooshing gestures cease as the hosts and Muller arrive at the creation of 'element number 26 … Iron' (30:30). The deep background ambience stops, with the relative absence of sound indicating a change or idea of renewed significance, and the listener hears a reverberant impact redolent of an iron gate, or metallic surfaces scraping together. While elemental iron has no resemblance to the object that this sound conjures in the listener's mind, it has the effect of relating the concept to our real-world understanding of iron, and its use in our everyday lives.

Later, Muller and Abumrad jointly describe the impact of the formation of iron upon the star: 'Everything starts to collapse… Gravity takes over…' (31:10). A previously heard low, ambient noise returns and begins pitch shifting downward; a weighty and languid sonic gesture which suggests increasing gravity. Of course, these sounds are not 'real', but the sonic illustration evokes a mental image of the supernova's growing mass. Abumrad puts it well when he says, 'even though we know there are no sounds in space, for the purpose of your enjoyment, we present to you… the supernova' (31:50), followed by a forceful explosive sound, conjuring images of a large star exploding outward. While adding a sense of immersion and enjoyment to the explanation, it can be argued that supplementing this scientific recount with sound design elements also enhances engagement and promotes an alternative, more tangible conceptualisation within the listener.

As is suggested by Abumrad's final comment, the goal of these sonic illustrations is not to communicate a realistic depiction of what these phenomena might sound like to the human ear. Had we the capacity to hear these events in the vacuum of space, there is no reason to believe that a realistic sound depiction would convey anything intelligible to a human listener. Instead, Radiolab's sound design draws on our anecdotal recognition of certain sounds, a process which might be deemed 'transcontextual' listening made possible by our 'identifying with them [the sounds] … and reinterpreting their meaning in their new musical context' (Smalley 1997: 110). Certain movements, timbral and textural evolutions, will remind the listener of feelings and movements in their own body which have accompanied or produced such sounds (Smalley 1997).

For example, a 'whoosh' sound evoking atoms smashing together will most likely evoke a strong visual of objects travelling rapidly through the air. This is a result of our anecdotal experience of such a sound in the world; the listener has learned that an object which *whooshes* has been thrown or otherwise launched with force, travels unhindered through a space, and is perhaps worth paying attention to (is it moving rapidly towards *me*? Let's follow its trajectory!), therefore creating an engaging and memorable mental image of the process.

19 See https://radiolab.org/episodes/elements. Accessed 27 May 2022.

The success of RadioLab's sound design, as well as that of science-focused contemporary music (science in music, science in sound, etc.), inspired us to create entertaining, sonically illustrated descriptions for the benefit of science education. As a medium for communicating broad scientific ideas, this type of sound design does not fall under current definitions of sonification, sound diagram, or sound effect; this led us to develop a new classification for sound-based education tools to accommodate this specific communication style, the *Sonaphor*.

Introducing the *Sonaphor*

The *Sonaphor*–a portmanteau of 'sonic' and 'metaphor'[20]–is a new sound-based learning tool featuring the use of dialogue, sound design, and musical content to introduce foundational scientific concepts to audiences. The four *Sonaphor* examples presented in this manuscript were designed specifically for the first presentation of the selected scientific concepts in secondary science classrooms. In an engaging and memorable format, we guide the listener to construct a dynamic three-dimensional mental image of a concept, structure, or process that would more traditionally be communicated in the classroom through visual and gestural modalities. We theorise that by allowing the listener to actively construct the mental image themselves, the *Sonaphor* may enhance understanding, as well as increase engagement and appeal through the enjoyment of sound design. The following section provides insight into how an iterative, non-hierarchical system encouraged rich discussion and awareness of the ways different people 'visualise' sound, and the various theoretical backgrounds and perspectives which contributed to the final iterations of these *Sonaphors*.

Sonaphor Structure

Each *Sonaphor* is composed of multiple sound-based elements. Spoken word, sound design, and an accompanying diffuse soundscape are layered together to illustrate a dynamic image of a scientific concept.

The role of the script is to guide the listener's interpretation of the designed sounds, direct their attention to important elements, foster emotional connections, and encourage the listener to interact actively with the *Sonaphor*. The sound design involved the creation of 'sound objects'[21] to represent individual atomic or

[20] Our team briefly considered the name 'sound diagram', but we needed to differentiate this new product from the important and established work of sonifying visual diagrams to make them accessible to people with low vision. We would also like to acknowledge the use of the phrase 'sound metaphor,' or 'sonic metaphor,' by Gershon (2011, 2018) noted in our reading during the preparation of the manuscript and after we named our *Sonaphor*.

[21] First discussed by musique concrète composer Pierre Schaeffer, and described in detail by his contemporary Michel Chion, the 'sound object' refers to a 'fragment' of recorded sound, to be perceived separately from any assumed 'causal', physical/acoustic, or 'anecdotal perception' (Chion 2009: 11–14). The act of objectively perceiving and analysing a sound object for its aesthetic qualities is termed by Chion (2009: 29) as 'reduced listening'.

subatomic elements described in the script. Using acousmatic and semiotic theory, the sound designer (AW) gave these objects voice and movement, reminiscent of the main characters in a radio play. In this paper, we will refer to the grouping of narration and responding sound objects as 'sound cells' (Fig. 2).

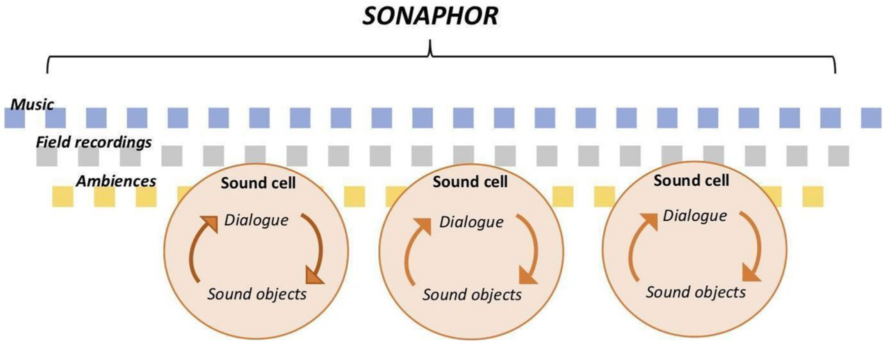

Fig. 2 Visual depiction of an exemplar *Sonaphor* structure. The *Sonaphor* alternates between spoken script and illustrative sound design, often contextualised by ambient drone, music, or field recordings, depending on the scale (macro to quantum) discussed

The final layer of diffuse soundscape is evocative of space, and used to clearly communicate the current setting to the listener, whether that be in the real, observable world (through the inclusion of ambient field recordings), or in the impossibly tiny 'nanoworld' (which might be evoked through low, layered drones and cavernous reverb, as in *The Atom* at 0:35).

Our First *Sonaphors*[22]

In initial explorations of the *Sonaphor*, we chose to focus on two foundational chemistry concepts: scale and the atom. These two ideas quickly split into four as we considered the cognitive load of the listener when deciding on the complexity of each *Sonaphor*. As noted by Bennett (1999: 50–51), sound-based diagrams seem to have more success when presenting users with simpler representations of diagrams, as opposed to more complex representations that rely heavily on the user's internal memory, i.e. their ability to identify and recall various diagram elements. The four final *Sonaphors* are detailed below.

Listen Up[23]

This script emerged after reflections from our science educators on key challenges of science education and communication: making science relevant by connecting it

[22] See https://github.com/alintheopen/SCOPE/milestone/2. Accessed 27 May 2022.

[23] See https://github.com/alintheopen/SCOPE/issues/18. Accessed 27 May 2022.

to real life (Cooper and Stowe 2018; Goodrum and Rennie 2007; Joubert et al. 2019; Lowyck 2014). Hence we start the *Sonaphor* experience with an introductory script placed in a familiar and tangible world, and prompt further interest by asking questions (e.g. Fig. 3).

Have you ever wondered what all the things that make up the world around you are made of? Right down to the structures that your eyes can't see?

Fig. 3 Excerpt from *Listen Up*

The Nanoscale[24]

The purpose of *The Nanoscale* is to support listeners to grasp the scale of our first *Sonaphor* series. Scale is relevant for all branches of science, as it is crucial for understanding the 'immense size of the cosmos, the minute size of molecules, and the enormous age of the earth' (American Association for the Advancement of Science 1993: 276). Despite its importance, immense differences in magnitude are extremely challenging to truly comprehend (Resnick et al. 2017)–hence the need to explore its comprehension through sound. With our commitment to providing a connection to the everyday for our listeners and a sense of playfulness and humour throughout our scripts, we placed *The Nanoscale* in the context of a typical Australian swimming pool (Fig. 4), zooming down from the familiar, to the foreign quantum realm.

So just how small are atoms? To understand more about their size, let's start… at… the swimming pool?!

Fig. 4 Excerpt from *The Nanoscale*

The Atom[25]

The atom is the fundamental unit explored in the field of chemistry but is too small for humans to see. Thus, we must imagine looking at, or inside atoms in order to 'see' them. There are many different ways that chemists can visualise, or model the atom; experts are adept at choosing the model which best supports their approach to a research question or educational context (Justi and Gilbert 2000). In this *Sonaphor*, the aim is to explore constituent parts of the atom that are known and present in all models–that is, the protons, neutrons, electrons, and their relative charges.

[24] See https://github.com/alintheopen/SCOPE/issues/19. Accessed 27 May 2022.

[25] See https://github.com/alintheopen/SCOPE/issues/20. Accessed 27 May 2022.

The Bohr Model[26]

The Bohr Model of the atom, or so-called planetary model, depicts the protons and neutrons clustered into a nucleus at the centre of the atom, with electrons 'flying' around the nucleus in discrete circular or elliptical orbits. We chose to append the Bohr Model of the atom to the Atom *Sonaphor* as it is the model most commonly used for school educational purposes (Justi and Gilbert 2000). It is generally accepted as the appropriate model for young people's initial introduction to the atom, and the discrete electron orbitals are sufficient for introducing learners to chemical bonding (Stevens et al. 2010).

Navigating the Interdisciplinary Space

The *Sonaphor* represents a mediation between traditionally separated fields; it is a learning tool which translates postdigital theory into practice by redirecting existing technologies from one field to open up new, meaningful ways of learning in another. This translation of theory into practice was possible due to the composition of our team with experts who each embody the spirit of the 'artist-researcher-teachers' (Alexenberg 2008: 20) in the diverse fields of educational theory and practice, chemistry education, public engagement, contemporary musicology, classical performance, and music technology. This created a shared understanding and intention within the project. While acknowledging a certain level of compromise was necessary at each stage, the differences in our experiences offered 'great potential for discovery' and catalysed 'creative potential and new ideas' (Hermann et al. 2011: 2).

In this process, the artist (AW) played a particularly important role as 'intermediary'. The ideas, thoughts, and feelings of each team member were directed towards her, and in the way suggested by Alexenberg (2008: 15), she found ways to form connections between our contributions to create an aesthetic experience that conveyed the desired meaning (the final *Sonaphor* product).

We note that the unique experiences of our team have woven themselves through the whole *Sonaphor* project 'cooperation, communication and interaction' through (Alexenberg 2008: 16). Thus, if another team were to create their own *Sonaphors*, while the basic production framework may stay the same, their collaboration would result in different artistic outcomes.

We established a culture within the team where all suggestions were considered and investigated in regular, semi-structured team feedback sessions. These allowed for free-flowing conversation about the mental images conjured by the *Sonaphors* in each individual's mind. Sessions typically began with a brief overview of the progress on each *Sonaphor*, a group listening session, and subsequent discussion where each listener would list positive or effective aspects of the *Sonaphors*, and identify

[26] See https://github.com/alintheopen/SCOPE/issues/21. Accessed 27 May 2022.

aspects of the narration and sound which did not achieve a potent mental image. Examples of elements which were discussed include:

- comprehensibility of the sound design;
- clarity of the mental image evoked (i.e. lack of ambiguity in the resulting image);
- script changes that might facilitate the *Sonaphor* composition;
- 'engagement factor' and tone of script delivery.

Communicating about sound and sound behaviours proved to be a particular point of interest among the team. One of the particular joys–and challenges–of working with a diverse group of interdisciplinary researchers is the vast and differing vocabulary used to describe similar concepts, as well as different problem-solving processes (Hermann et al. 2011). This is further compounded as the way in which individuals visualise and talk about sound is inherently subjective (Blackburn 2010; Smalley 1997) and lacking a shared vernacular across different fields (Oliveira 2018). Some researchers relied on onomatopoeia and physical gesture to illustrate their understanding of what a particular subatomic character *should* sound like to them, while others used terminology from the fields of musical semiotics, product design and acousmatic music–necessitating further explanation.

An example of our creative process–and some of the vocalisations and spoken descriptions which were used to travel towards the final *Sonaphor* sounds–can be found in discussions around what a proton and neutron *should* sound like (the final sounds can be heard in *The Atom* and *The Bohr Model*). The science educators (GF and AM) decided that the relative size and charge of these particles were important to highlight within the sound design, thus setting the challenge for the sound designer (AW) to create novel sounds which clearly communicated these qualities over a number of iterations. Figure 5 demonstrates the difficulties of describing abstract concepts and novel sounds in language across disciplines.

The electron sound is too big and too loud compared to the nucleus, the sense of scale difference isn't there. The electron needs to sound smaller and the nucleus needs to sound bigger.

We love the sound of the protons, but the neutron has a 'double' sound that we don't like. We like that you've tried to create a charge on the proton, but we are not sure about the 'electrical fuzz' nature of it - it sounds too much like electrons and electricity. Maybe the positive charge (proton) should have a 'zing' or 'charge' sound but not an electricity sound. The electron should sound like 'zzzzzzzzzzz', like a light going off in a creepy movie. The proton should be more like a light that's flashing in Stranger Things when Eleven arrives. 'Bonnnnnnggg'. Warmer and bigger. We can also give proton an echoey thing. The neutron should be more like a snooker ball in that sense of - the noise doesn't last, it happens quickly, it's not radiating out at all. The noise is gone and doesn't hang around. It's dull, empty? Full? Not sure which will sound better.

Fig. 5 Excerpt from listening session discussion between GF and AM on 19 November 2021, edited for clarity

An Iterative Methodology

The process for creating the *Sonaphor* can be distilled into the following steps, and serves as a loose framework for future *Sonaphor* constructions.

1. Full team discusses the concept for the *Sonaphor*.
2. Science educators (GF and AM) proposed topics for the *Sonaphors*, the full team discusses the feasibility of our ideas.
3. Secondary science educator drafts a script (GF), with further iterations and finalisation completed in collaboration with science communicator and tertiary educator (AM).
4. Together, the educators and sound designer (AW) identify all relevant 'characters' (whether that be subatomic particles or units of measurement) and the changes or behaviours they will undergo which need to be represented.
5. Sound designer assigns previously developed sound objects to each character or develops new sound objects to represent new characters.
6. Sound designer assesses how each character will undergo *change* to communicate chemical concepts through time (i.e. through the character's behaviour, location within the sound space, interaction with other characters, etc.). Educators may put forward ideas on how this will sound. The sound designer determines which parameters will communicate the change (i.e. change in pitch, timbre, spatialisation, etc.).
7. Sound designer 'composes' the first iteration of the *Sonaphor* by recording the script, then arranging script and sound objects to create a series of sound cells. Appropriate foley, ambience, and musical elements are brought in to create backdrops for these sound cells.
8. The entire team reviews the first draft of the *Sonaphor* and discusses its efficacy, noting feedback from all members of the group. Feedback includes the script, sound design, ambient elements, and overall visuals evoked from their combination. Points for revision or further exploration are noted.
9. If necessary, educator and communicator revise script and re-issue to sound designer with accompanying suggestions for sound design. If necessary, the sound designer revises sound or musical elements.
10. The entire team reviews the next iteration of the *Sonaphor*, either providing further constructive feedback and suggestions or signing off on the finished *Sonaphor*.

Using Sound to Construct Visualisations

Visual representations have, for a long time, been considered essential for thinking, learning, and communicating in chemistry (Gilbert 2008; Jones and Kelly 2015; Kozma and Russell 2005; Lemke 2005; Luisi and Thomas 1990; Prain and Tytler 2013; Tuckey and Selvaratnam 1993). The *Sonaphor* use of sound to create memorable images in the mind of the listener extends naturally from this practice in chemistry education. Chemistry has a reputation for being difficult to learn; this is mostly attributable to its dealings with abstract concepts,[27] and the need to interpret symbolic representations of these concepts (Gilbert 2008; Johnstone 1993). Thus, one of the most important but difficult skills in chemistry is the ability to imagine dynamic, three-dimensional representations (Abdinejad et al. 2021; Gilbert 2005; Johnstone 1993; Prain and Tytler 2013; Tuckey and Selvaratnam 1993).

Chemistry students are often expected to internalise and apply the visual representations presented to them in class (Tippett 2016). These representations usually take the form of either 'chalktalk' (two-dimensional diagrams drawn or projected onto a board or screen, accompanied by symbolic or gestural representations of movement) (Danielsson 2016; Lemke 2005) or diagrams in textbooks accompanied by descriptive text (Jones and Kelly 2015; Tasker and Dalton 2006). These representations are inherently limited in the information they can represent or communicate and have been increasingly found to contribute to chemistry students' misconceptions of chemical concepts (Danielsson 2016; Gilbert 2005; Tasker and Dalton 2006). More recently, animations of chemical concepts have proven useful in addressing some of the limitations of static models, particularly those which are three-dimensional and allow for interaction such as zooming in and out to view chemical structures at different scales (Abdinejad et al. 2021; Tasker and Dalton 2006; Venkataraman 2009).

However, simply showing students diagrams and expecting them to learn from them is a transmissive mode of teaching, and inconsistent with a constructivist understanding of learning[28] (Tippett 2016). Reflective of the neoliberal habit of engaging learners in 'academic labour' rather than 'intellectual work' (Cormier et al. 2019), this focus on memorisation and regurgitation is associated with reduced student interest and engagement in learning (Savin-Baden and MacKenzie 2022). In preparing young people to be creative and critical thinkers in the postdigital future, the science education community needs to identify ways of engaging learners in scientifically accepted models as 'concepts' rather than 'information' to be learned. This is not an easy task–the challenges

[27] In referring to abstract concepts, we mean the structures and behaviours of particles that are too small for the eye to see, even with a microscope. Even though the structure and behaviour of these particles dictate the properties of solids, liquids, and gases at an observable scale, they are not encountered in this sub-microscopic form in people's everyday lives.

[28] Constructivist theories of learning state that meaningful learning relies on the learner actively constructing meaning from instructional materials and connecting new information to their prior knowledge (Ausubel 1968; Bodner 1986; Novak 2010; Vygotsky 1978).

involved in finding the balance between ‘correct’ and ‘learner-owned’ is highlighted by the scarcity of successful examples (Gilbert 2008).

In the spirit of Marcel Duchamp, we suggest using sound to break free from the constraints of the visual (Judovitz 2010). Using sound, educators have a scaffold which provides the ‘must-haves’–while the absence of visual cues leaves the learner with sufficient agency to embellish their internal visualisation in their own unique way. Hence, listeners are afforded the freedom of creating something that is uniquely their own–while still retaining the characteristics which make it a scientifically correct model.

Script Generation

The first iterations of the *Sonaphor* (commenced in 2020) did not involve spoken dialogue, which left the designed sounds open to vastly different interpretations. Therefore, we added descriptive dialogue which began to play an important role in directing the listener’s interpretation of the designed sounds. In the final iterations, each individual sound object or gesture appears closely linked to the script component–in *synchronicity* (Fig. 6). This also follows recommendations of science education researchers Tasker and Dalton (2006), who found that the key features in scientific animations must be highlighted in some manner to ensure that learners are able to extract critical information.

But flying through that empty space are some tiny particles. And every so often one zips past.
electron zipping sound - like the snitch

Fig. 6 Excerpt from *The Atom*

As the focus of the *Sonaphor* turned towards an *immersion in the experience* of the scientific concept, the scripts took on new significance. The need for the listener to actively imagine the visuals of different sonic events and ‘characters’ required *imaginative immersion*–characterised by the listener becoming ‘absorbed with the stories and the world’ (Ermi and Mäyrä 2005: 101)–in this case, the sub-microscopic and nano worlds, as well as the different subatomic elements which interact there. Hence, creating an immersive script became an essential consideration. We used a narrative style and second person invocation of the listener to create engagement and emotional connection (Joubert et al. 2019) (Fig. 7).

We are now floating in the centre of an atom.
Notice that there’s a looot of empty space around us.
silence?

Fig. 7 Excerpt from *The Atom*

The scripts were designed using a social constructivist framework (Vygotsky 1978).[29] This was achieved by establishing a conversational, light-hearted, and almost dialogic relationship between narrator and listener (Fig. 8). This back-and-forth is enhanced further by the insertion of Greek Chorus-style interjections (such as can be heard at 0:11–0:16 of *The Bohr Model*). As the listener is invited into a conversation with a personable narrator, they are encouraged to envision a scene in their mind, rather than passively absorb the information. This is a key strength of our design, as there have been few tools developed which actually support learners to construct their own representations (Gilbert 2008)–despite abundant evidence that learners benefit from opportunities to construct their own internal representations, rather than remembering an external visualisation (Ausubel 1968; Bodner 1986; Novak 2010; Tippett 2016).

Have you ever wondered what all the things that make up the world around you are made of? Right down to the structures that your eyes can't see?

If we move further into the atom to its very centre, we can see a tight cluster of two different types of particles.

Fig. 8 Excerpts from *Listen Up* (above) and *The Atom* (below) scripts

Perspectives from Semiotics, Contemporary Music, and Acousmatic Music

In designing the sounds for each *Sonaphor*, it was necessary to create a balance between listener engagement (achieved through musical creativity), mnemonic efficiency (making the sounds memorable and symbolism identifiable), and semiotic efficiency (making the purpose or symbolism of sounds easily recognisable). We drew primarily from the fields of semiotics and acousmatics in designing the final *Sonaphors* and we outline our approach here.

Designing 'Sonic' Particles–Drawing on the Familiar, Navigating the Unfamiliar

Musical semiotics provides us with a useful perspective to explore sound-based learning tools such as the *Sonaphor*. The study of semiotics refers to the study of signs which denote or connote further meaning. When applied to music, musical sounds (sometimes referred to as 'musemes'–the smallest units of musical information) are used to denote paramusical beings (Chandler 2007; Tagg 1987). Using the Saussurean model[30] of sign construction, the *Sonaphor* essentially creates new 'sign

[29] In common with constructivist theories of learning (see Footnote 7), social constructivist theories involve the learner actively constructing meaning. In addition, it is asserted that the nature of learning is collaborative or dialogic (Vygotsky 1978), hence our decision to create a conversation-like feel with the narrator.

[30] Developed by Ferdinand de Saussure, this model splits the concept of the 'sign' into two main elements: the 'signified', or meaning behind the sign, and the 'signifier', the form which the sign takes which can also be termed a 'sign vehicle' (Chandler 2007: 14).

vehicles' which compel listeners to attach our designed sound objects to specific scientific bodies (e.g. electrons or protons) (the 'signified') (Chandler 2007: 33). We also draw from Smalley's (1997: 110) idea of 'source bonding' from acousmatics, which refers to the listener's tendency to 'relate sounds to supposed sources and causes', a subjective experience relying on the listener's lived understanding of sound and its origins. This individual nature of sound interpretation and source bonding both fascinated and challenged our team to find a 'path of best fit' through the available sound worlds for each *Sonaphor*, and the design of recurring atomic elements.

There are rich examples of the usefulness of sounds as symbols within product sound design, such as *auditory icons* which link digital processes with their real-world counterparts–a ubiquitous example is the crumpling paper sound triggered upon emptying the trash icon on a Macbook–and *earcons*, abstract sounds that symbolise actions or alerts and are learned by the user of a product–such as the beep of a microwave timer (Langeveld et al. 2013). While it can be said that the *Sonaphor* employs 'scientific earcons' to symbolise different characters, we have also intentionally used existing sound associations.

For example, electricity is commonly associated with a 'zap' sound or a buzzy timbre, so using these attributes to describe electric components will help to create a 'semantic link' between designed sound and real-world experience (Langeveld et al. 2013) and hence decrease the cognitive load required to remember its meaning (Bennett 1999). Thus, we have used a high-pitched, shimmering sound object to represent the electron. Of course, this approach relies heavily on the experiences of listeners (Smalley 1997), making the sounds we have chosen specific to the culture and collective sonic experiences of the team. By coupling the sound and script (Fig. 9), the narrator ensures the listener attaches specific meaning to the previously unheard sound.

> *...Flying through that empty space [inside the atom] are some tiny particles...and every so often one zips past. That is an electron.*
> ****whoosh****

Fig. 9 Excerpt from *The Atom*

The use of a high-pitched, shimmering sound to represent the electron can also be viewed as an example of third-level surrogacy described by Smalley (1997: 112), and is similar to the technique used by RadioLab to symbolise the black hole in *Elements* (2021). The sound chosen is neither the sound of electrons moving, nor akin to the likely sound of electrons. Instead, the sound is *behaving* like electrons moving (Blackburn 2010; Smalley 1997). In considering the Peircean sign system,[31] the electron sound floats between three categories: indexical,

[31] Developed by Charles Sanders Pierce, this model splits the concept of the 'sign' into three elements: the original concept or object which the sign aims to represent; the 'form which the sign takes' (the 'sign vehicle'); and finally, the resulting interpretation of what the sign vehicle represents (Chandler 2007: 29).

iconic, and symbolic (Chandler 2007). Discussing the Piercian sign system, Oliveira (2018: 343) suggests that sound in general can be thought of as indexical. Although the zappy sound of the electrons closely resembles highly recognisable sounds that electricity can make (making it an indexical or iconic sign), it doesn't *actually* resemble the sound of electrons orbiting around a nucleus (making it a symbolic sign, and requiring the designer to make the meaning clear to the listener) (Chandler 2007: 36). By conflating previously unfamiliar events with very recognisable sound representations, we force an agreement between the narrator and listener that an electron zooming around an atom gives off a Doppler effect–style volume envelope and sounds 'zappy'. Thus, our high-pitched sound object becomes a sign vehicle for an electron.

In the examples where new sign vehicles were created, it was even more important to signpost this to the listener in the script (Fig. 10).

If we move further into the atom to its very centre,
p+n sound faint and far away and getting closer
we can see a tight cluster of two different types of particles.
p + n sound clear

This cluster is called the nucleus. Unlike the almost weightless electrons, the two types of particles in the nucleus do have mass. This means that the nucleus is the place with almost all of the atom's mass.

The two particles that make up the nucleus are called protons and neutrons. Protons are positively charged. ***proton sound***

And neutrons are neu-tral; they have no charge. ***neutron sound***

Fig. 10 Excerpt from *The Atom*

Using Sound to Represent the Behaviour and Movement of Particles

The concept of the 'anaphone', developed by Philip Tagg, is a sonic semiotic tool in which the musical stylisation of sound represents something that 'exists outside the discourse of music' (2012: 487); for example, the use of audio effects or timbres which suggest an image or movement.[32] Anaphones can be broken into three main

[32] An example is found in TMBG's *Meet the Elements* (2009), which includes unusual instrumentations and found sounds in percussive roles to further enhance the listening experience. While singing, 'Did you know / Elephants are made of elements?' (1:50) a braying, low brass accompaniment can be heard, suggesting the trumpeting of said anima, by way of a sonic anaphone. Examples from Western art music include thunderstorms evoked by Beethoven's *Symphony No. 6 in F Major* (1808), the sunrise painted by the introduction of Mahler's *Symphony No. 1* (1888), and the animals brought to life by Prokofiev's *Peter and the Wolf* (1936).

categories–sonic, kinetic, and tactile. The *Sonaphor* uses all three of these anaphone types in different applications. ‘Sonic anaphones’ denote the ‘musical stylisation’ of a non-musical sound (Tagg 2012: 487). For example, *The Nanoscale* employs multiple sonic anaphones to differentiate between magnitude and *lightness* of different scales, while *Listen Up* uses an increase in arpeggiation rate, stereo width and shifting pitch to suggest an event of rapid multiplication (heard while discussing the astronomical amount of atoms which are found in one teaspoon of water from 1:20 to 1:34).

‘Tactile anaphones’ represent the sense of touch or evoke an associated haptic feeling; Tagg (2012: 494) provides the example of smoothly bowed orchestral strings giving the impression of a ‘thick, rich, viscous effect’. In our work, listeners can hear an evocative *impact* sound in *The Bohr Model*, describing Bohr’s merging of several ideas into one atomic model (0:30–0:34). This gives the impression of many disparate units being slammed together into one central object–a blunt illustration of the research process, perhaps, but certainly evocative!

Finally, Tagg (2012: 498–500) describes ‘kinetic anaphones’, referring to a musical sound that connects to the experience of movement and can occur in three specific ways: ‘gross-motoric’, such as envisaging ‘dragging, pushing, pulling’ which can be heard in the *whooshing* of air running past the listener as various *Sonaphors* zoom in to different scales; ‘fine-motoric’, light or delicate movements such as ‘blinking, glittering, shimmering…’ (heard in *The Atom* while describing quarks at 2:20), or ‘holokinetic’ which relates to the movement of a body through space, which we have used to create a circular orbit for the electrons in *The Bohr Model*. The use of movement through the *Sonaphors* was a significant contributor to visualisation and requires further discussion through the lens of acousmatic composition.

Using Acousmatics to Create a Spatial Experience

The ability of sound to evoke embodied and visual memories was central to our creative process and informed our design of the ongoing behaviour (i.e. trends of movement, perhaps even to be thought of as individual *personalities*) of different sound objects. Alongside behaviour, the exploration of *space* and spatial experience are central to the acousmatic medium (Smalley 2007). The movement of each sound object and character *around* the sound space, through time, is one of the most important and unique qualities that the *Sonaphor* could provide to the scientific learning experience.

Not departing from visual representations altogether, we found it helpful to elucidate the mental images evoked by the sound design through illustration. Figure 11 shows the behaviours and movement (dubbed ‘spatiomorphology’ by Smalley (1997: 122) of the electron around the atomic nucleus (not shown) in *The Atom* (as can be heard at 0:58), sketched by the sound designer (AW). This diagram is inspired by the guidelines for acousmatic visualisation put forward by composer Manuella Blackburn (2011: 13), and also takes inspiration from the representations of height and depth explored by Moore's (2016) 'soundbox' diagrams.

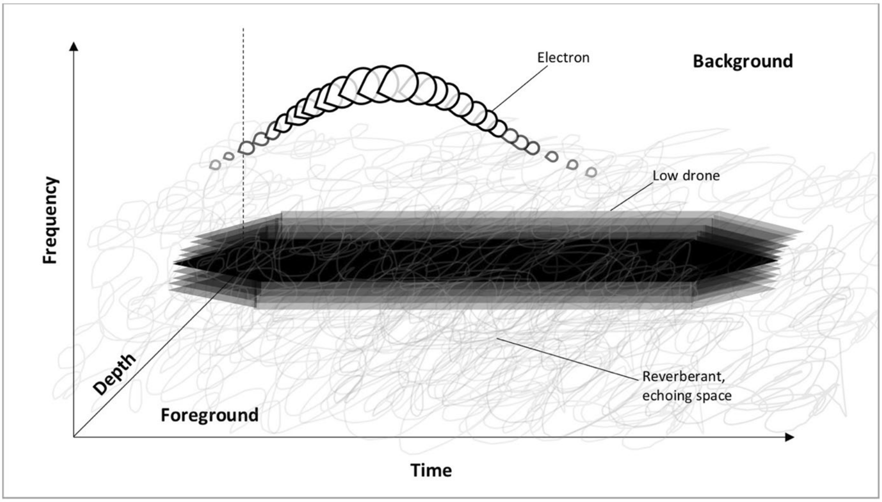

Fig. 11 The spatial and spectral movement of the electron sound object through time, as heard frequently in The Atom. The diagram format and inspiration for sound shapes is taken from Blackburn (2011: 8, 13). Readers should note that left–right movement (or stereo panning) is not shown in this diagram

The electron is panned in a way which suggests an elliptical path around a central point (in this case, the nucleus).[33] The electron is high, with a thin, metallic, and shimmering quality to its sound. As it moves across the sound space from left to right, its pitch shifts downward to suggest, through a Doppler effect–style psychoacoustic phenomenon, that the electron is moving away from the listener. In the background of the soundscape the listener can hear a sustained expansive drone at a much lower frequency and heavy reverberation drenching the sound stage; not only filling out what would otherwise be silent, digital space, this drone suggests vastness (which is further suggested by the script at 0:42, seen in Fig. 12).

If hearing this ambience through the lens of Smalley's spatial vocabulary, we might describe this as a 'generalised ground' (2007: 36) on which more discrete textures and sound objects may act. While the nanoscale often features reverberant

Notice that there is a loooot of empty space around us!

Fig. 12 Excerpt from *The Atom*

[33] In future iterations, the use of binaural spatialisation may be used to enhance the elliptical shape of the electron's trajectory.

ambiences and drones, the macroscale is relatively dry and populated with real-world field recordings (exemplified well in *The Atom*), allowing us to create the impression of the listener being within an imaginary 'bounded space' (Smalley 2007: 42) when exploring the atom–and hopefully, increasing the sense of immersion within the conjured mental image.

Bringing It All Together: Painting One Sonic 'Picture'

As seen in Fig. 2, we combined individual puzzle pieces–dialogue, sound objects, their various imparted behaviours and associations–into an holistic image of the scientific phenomena through the construction of *sound cells.* When combined with contextualising elements such as music, ambience, and field recordings, multiple sound cells make up the *Sonaphor.* These sound cells reflect the linguistic concept of a 'double articulation language' (Chandler 2007: 6, 249), whereby the meanings of individual sound objects (representing discrete subatomic particles) and their movements (gestures) are grouped consecutively, thereby painting a picture of a larger scientific phenomenon in both spoken word and sound. Our sound cell structure is comparable to Hermann et al.'s auditory scene (2011)[34] and Smalley's depiction of the Orbieu Soundscape (2007), as the listener chooses to either focus on the interacting sound layers as a monolith, or zone in on any individual sound object's identity, placement or movement. Likewise, the *Sonaphor* is a larger 'scene' of sound cells against a musical or ambient backdrop, each of which can be divided into the components of script or sound object. This modular construction tells the overall story of a concept or phenomenon in nanoscience or chemistry.

Sonaphors in Schools

Sharing the *Sonaphor*

Our vision is that *Sonaphors* will be flexible, living digital objects which can be deconstructed and rebuilt by creative teams, classrooms, or individuals around the world. Thus, the *Sonaphors* described in this paper and accompanying stems (containing existing dialogue and sound objects in both mono and stereo format) will be housed on the open collaboration website, GitHub,[35] where they are freely accessible and available for non-commercial use by others under CC-BY licence. Through this platform, artists and scientists will be invited to contribute their own interpretations of this *Sonaphor* collection. With just a microphone and Internet connection,

[34] Auditory scenes are described by Hermann, Hunt, and Neuhoff in their Introduction to *The Sonification Handbook* (2011).

[35] See https://github.com/. Accessed 27 May 2022.

young people, scientists, and educators from around the world will be able to replace the original *Sonaphor* narrations with their own.

As a result of this open collaboration, in a style resembling Yoga Buddhi Co. app Down Dog,[36] the final housing of this *Sonaphor* collection will include customisable narration. This increases the accessibility of the *Sonaphor* by decreasing language barriers and promoting visibility (or 'audibility') of people who have been historically underrepresented in science. Similarly, musicians and sound designers from a wide range of backgrounds and training will be invited to create their own sonic interpretations of the *Sonaphor* scripts and sonic characters, which will allow us to include options for different sound interpretations. The ability to customise all aspects of the aural experience maximises the potential to appeal to a wide range of listeners, therefore also maximising the range of listeners engaging with the scientific content.

The *Sonaphor* as a Tool Which Can Foster Postdigital Learners

The ability to visualise chemical concepts has long been considered crucial for engagement with chemistry (Gilbert 2008; Jones and Kelly 2015; Kozma and Russell 2005; Lemke 2005; Luisi and Thomas 1990; Prain and Tytler 2013; Tuckey and Selvaratnam 1993). However, due to the difficult nature of this task, there is a paucity of tools available to support the development of visualisation skills (Gilbert 2008). This challenge may be why teachers often revert back to transmissive teaching models, which are ineffective for many young people (Savin-Baden and MacKenzie 2022). The *Sonaphor* represents a significant addition to the pedagogical repertoire of science educators and science education researchers, in that it supports learners to build a three-dimensional, dynamic space in their minds' eye that is both 'scientifically correct' but also their own. *Sonaphors* thus have immediate application in introductory chemistry classrooms, where they could complement or replace the current suite of visual diagrams that are the backbone of our current educational practice.

In addition to their educational potential in their current form, *Sonaphors* present an interesting new possibility for learners to construct their own representations of chemistry concepts. Rather than engaging with a fixed *Sonaphor*, learners may be called upon to locate or create their own sounds to illustrate their scientific understanding. Just as student-generated drawings have been deeply explored as a vehicle for enhancing learning and allowing teachers to understand the internal representations learners hold about concepts (Chang et al. 2020; Prain and Tytler 2013; Tippett 2016; Van Meter and Garner 2005), Crowther (2012) suggests asking students to write their own songs to illustrate scientific concepts. The *Sonaphor* is an extension

[36] A yoga practice app, Down Dog allows its users to not only change the type of yoga, practice duration, pace of narration and yoga flow, etc., but also to easily customise audio variables such as the language, accent, and voice type of the virtual instructor, the soundtrack genre, and even the mix of voice and soundtrack layers. The user has the agency to create their own bespoke experience, hence rendering the app and resulting yoga practice more engaging and relevant. See https://www.downdogapp.com/. Accessed 27 May 2022.

of this suggestion, moving the creative response into the territory of found and generated sounds.

Although the iteration of the tool that we present in this paper is inspired and enabled by digital technology, in the spirit of 'postdigitalism' it is by no means tied to any particular media (Cramer and Jandrić 2021), and can be used by, or re-created by any young person, in any classroom. Creating a sonic 'image' of scientific understanding does not necessitate the use of the digital: by exploring and creating new sounds in their classroom environments, learners could demonstrate their interpretation through live, sonic performance in an entirely analogue way. Alternatively, students could create a hybrid 'digitanalogue' (word coined by Ryberg et al. 2021: 418) *Sonaphor* which encompasses analogue and digitally recorded or altered sounds using readily available tools such as Garage Band[37] or free Digital Audio Workstations such as Cakewalk[38] (or, if centralised education licences are available, more instrument and effects-rich programs such as Logic Pro[39] or Ableton Live[40]). To promote collaboration between students, programs such as Soundtrap[41] enable simultaneous interaction on one project, and may therefore facilitate creative endeavours for student groups or those beyond the classroom limits, allowing anyone to create together from different locations.

We see particular strength in the utilisation of the *Sonaphor* concept to support learners to generate their own responses to learning. In its simplest form, the notion of privileging sound over the visual to share scientific knowledge is a subversive practice, and it allows educators and learners to respond to curriculum in de-centralised and classroom-specific ways in the spirit of 'curriculum improvisation' (Aoki 2004). The practice of non-hierarchical creation ensures that the student becomes, perhaps for the first time, the driver of their learning–assisted, but not directed, by digital technology. By allowing students to more freely interpret scientific concepts, the classroom voice of authority is quite literally returned to the student, encouraging a plethora of new responses which do not gate-keep according to 'prerequisite knowledge and skills, learning styles, and cognitive, emotional, and social development' (Fulgham et al. 2015: 43). Furthermore, freedom to imaginatively respond to taught concepts allows students to 'come up with answers that belong to them' (Cormier et al. 2019: 487), with important repercussions for the platforming of traditionally marginalised voices (Ahern 2022). In not only allowing, but encouraging diverse 'sonic expression' (Ahern 2022: 164), student-led *Sonaphor* creation actively subverts the problematic nature of pedagogies that enforce a single right answer or interpretation (Gallagher et al. 2021). This represents an important step in exploring the possibilities of 'more democratic forms of learning' (Jandrić and Hayes 2020: 289) and allows technology to act as an enabler of social change (Cormier et al. 2019: 484). This encouragement to bring students' own artistic preferences and context to the classroom also fosters positive personal

[37] See https://www.apple.com/au/mac/garageband/. Accessed 27 May 2022.

[38] See https://www.bandlab.com/products/cakewalk?lang=en. Accessed 27 May 2022.

[39] See https://www.apple.com/au/logic-pro/. Accessed 27 May 2022.

[40] See https://www.ableton.com/en/trial/. Accessed 27 May 2022.

[41] See https://www.soundtrap.com/pricing-education. Accessed 27 May 2022.

and emotional connections between learners and learning (Crowther 2012; Fawns 2019; Gallagher et al. 2021).

In the context of sonic construction, young people are provided with the space to play in the hybrid, postdigital realms discussed by Ryberg et al. (2021), and are given permission to push the boundaries of possibility. Through metacognitive reflection on their work and play, students could be encouraged to critically analyse ‘the role of technology in their own learning journey, and make informed choices to incorporate it meaningfully in learning’ (Savin-Baden and MacKenzie 2022: 554). From this place, it is not such a large cognitive step for students to begin noticing and interrogating technological developments and actions in the world around them (Alexenberg 2008; Cormier et al. 2019). Hence, the *Sonaphor* represents a concrete suggestion for the translation of postdigital theory into educational tools and classroom practices that work towards raising a generation of thoughtful, postdigital learners that are capable of re-imagining our future (Cormier et al. 2019; Savin-Baden and MacKenzie 2022).

Evaluating the *Sonaphor*

This paper presents theoretical arguments for the utility of the *Sonaphor* in classrooms. In the next stages of our project, we will investigate the efficacy of these sonic tools in supporting young people to develop conceptual understanding of chemical concepts in real classrooms. In this work, we will investigate whether the *Sonaphor* represents the expected shift from the ‘academic labour’ of rote learning chemical diagrams, to ‘intellectual work’ on the part of the learner (Cormier et al. 2019).

Conclusions

The *Sonaphor* collection begins a discussion about how postdigital theory can be used to guide the creation and implementation of new tools which can contribute to a postdigital science education. Educational technologies progress and change at an extraordinary pace, and it is important that schools incorporate these changes in thoughtful and critical ways, using technology to *advance* rather than replicating practice. It is our hope that the *Sonaphor* will empower science educators to move towards conceptual learning strategies, embracing all of the diversity that learners bring to the classroom, and facilitating young peoples’ growth as critical and creative users of technology. We envisage that through further iterations, collaboration, and evaluation, the *Sonaphor* and similar sound-based modalities will become a ubiquitous element of the pedagogical toolbox. By involving young people in the generation of creative sonic tools for learning, interrogating, and communicating, we can begin to instil critical, postdigital values and capabilities in young people. We see hope for the future of science education as an avenue for young minds to learn more about the world with individuality, musicality, and ears open to new possibilities.

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