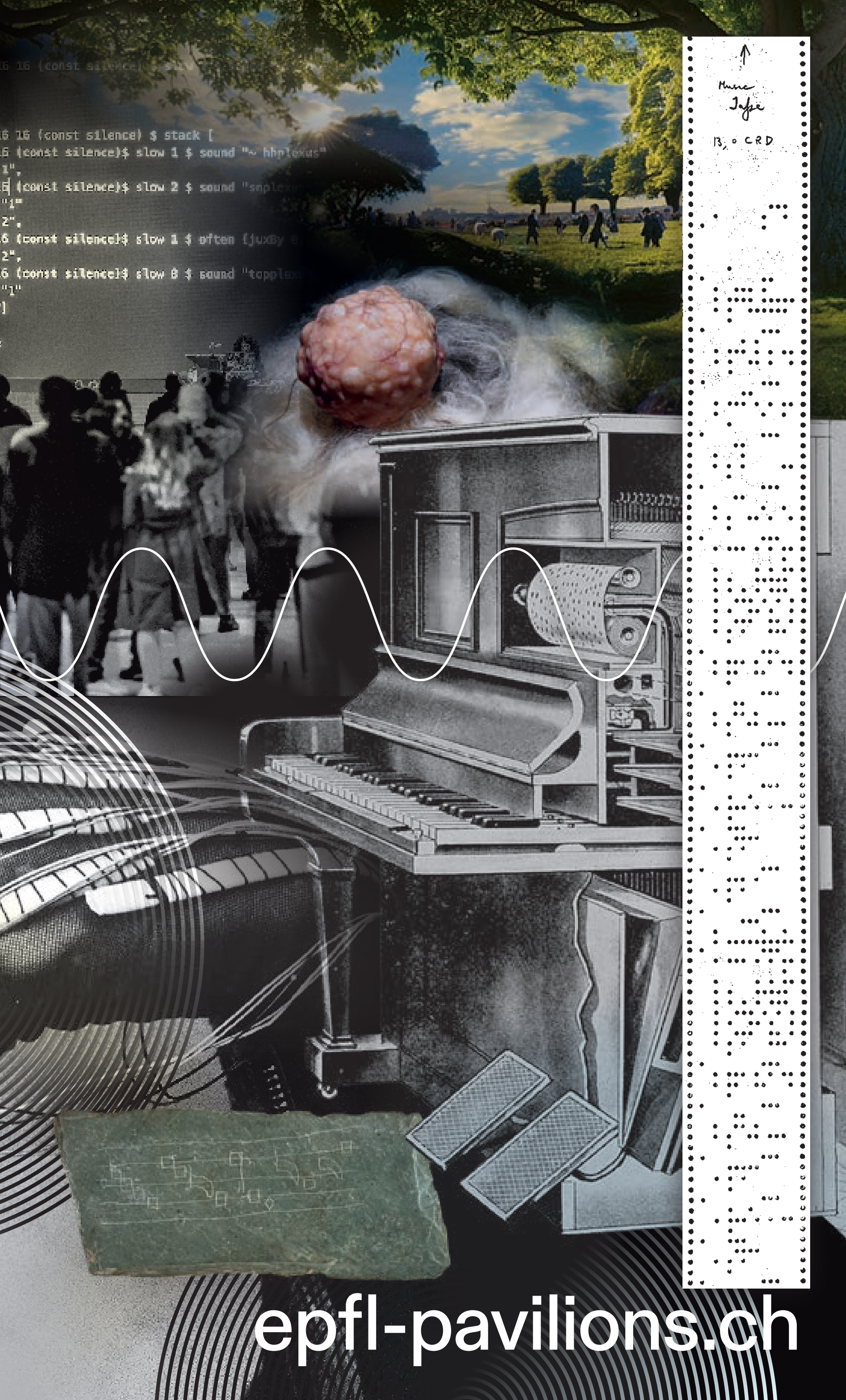
# Musica ex Machina

## Machines Thinking Musically

EPFL Pavilions

English Guide



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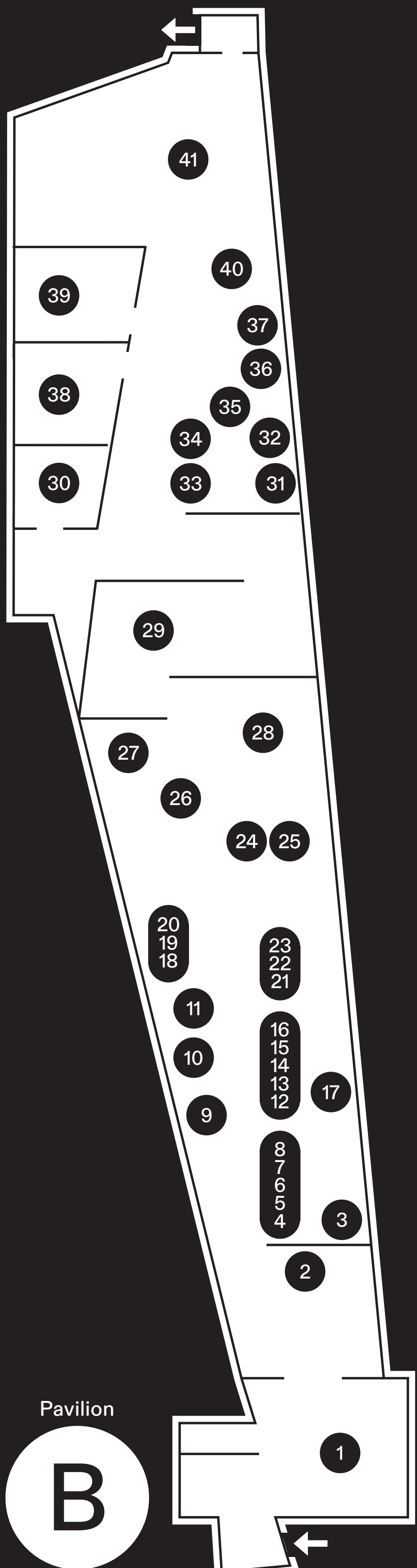
# Plan and installations

Pavilion B

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# Musica ex Machina: Machines Thinking Musically

From Ancient times to the present day, the nature of music has enabled it to be encoded mathematically and conceptualised algorithmically. Indeed, many musical structures are built around patterns and processes. Music is responsive to being modelled and manipulated by rules-based systems and, ultimately, by machines. Whether as symbolic or audio data (notes, processes or sounds), the representation of music invites the manipulation and elaboration of these distinctive features into works of greater complexity and wider imagination, such as the art music of many cultures.

*Musica ex Machina: Machines Thinking Musically* explores the intersection of computational thinking, mechanisation, technology, and music. The exhibition showcases human creativity in the complex relationship between machines, algebraic thinking and technological innovation. It demonstrates that there is no inherent dichotomy of 'expressive' music and what is sometimes called 'mechanical' or 'formalist' music. Music has an inherent technicity that is part of how we engage with it. *Musica ex Machina* selects objects to highlight and illustrate this rich and dense history to the present day.

The exhibition begins by exploring the original ways in which music has been coded and conceptualised algorithmically. Classical Greek astronomers developed early models of the universe, and the structure of music was thought to be modelled after these cosmic systems. In turn, music was conceived of as a way in which humans could touch the mind of God. Music is also discovered to be a common language connecting different cultures since every civilisation has developed music as a form of expression.

Mankind has always used the latest technology to create music, from metal strings replacing gut strings to the latest manufacturing techniques creating new instruments such as the piano. With the advent of mechanical devices, technologies were used to create and modify musical sounds automatically. Automated instruments and the mechanical clockwork devices of the Renaissance became the machines that could work with, or even replace, humans in the art of performance.

Following the invention of computers, early algorithmic composition experiments were used to generate new music. *Musica ex Machina* investigates the diverse approaches taken by composers who used machines to model their creative processes. Pioneering composers such as the Greek-French composer Iannis Xenakis, among many others from the mid 1950s, used machines to model compositional processes and pushed the boundaries of musical structure and composition practice. The exhibition explores the distinctive techniques by which randomness and unpredictability, at the heart of modelling creative thought, have been incorporated into composition and performance.

The latest developments in artificial intelligence (AI) are central to contemporary debates in music, debates that put human creativity in tension with the machine. *Musica ex Machina* takes a critical lens to examine the logical progression of this development as well as the potential limitations of AI. Importantly, a distinction is made between algorithmic style replication systems and genuine creative composition. This exhibition considers the extent to which machines can be seen as creative agents in their own right, particularly relevant with the latest AI advances, and exposes the ethical and philosophical implications of using machines to generate music. Can systems that have outputs completely derived from training data be truly creative?

While the exhibition is largely organised chronologically, there are four central themes that bind the exhibits together. The exhibition examines how systematic thinking and machines have been employed to generate and shape musical expression over the centuries through the following broad ideas:

Symbols, Spaces & Algorithms looks at how music has been represented symbolically and conceptualised in proto-computational ways: ancient systems such as the harmony calculating tool of Guido d'Arezzo's hand through to contemporary symbolic manipulation and non-Western algorithmic music traditions.

Automating the Human illustrates the music machines, automata, and automated instruments from the 18th century onwards that brought mechanisation into the human realm of musical performance and composition, where some human activity was replaced by a machine.

Music as Information and Data focuses on the emergence of recording technologies that transformed musical sound into data, as well as early electronic instruments and the use of computers to algorithmically generate music by pioneers like Lejaren Hiller, Iannis Xenakis, Pietro Grossi, Clarence Barlow, and Gottfried Michael Koenig.

Body, Mind & Machine explores interactions between musicians and technology through sensing, sensors, and artificial intelligence, featuring works by artists who incorporated interaction into their creative process.

*Musica ex Machina: Machines Thinking Musically* aims to inspire critical thinking about the ways in which composers have systematically approached music and how technology is shaping our understanding of music and creative expression.

## Exhibition's Playlist

# 1 *Polyp* 2022–2024

Interactive sound installation: 3 spheres of 40 cm ø made of silicone & yak hair, edgeML system. Nesting mechanism: wire armature and synthetic yak hair.

## Marek Poliks & Roberto Alonso Trillo

are creative technologists, respectively working in Minneapolis and Hong Kong.

*Polyp* consists of three silicone sculptures, which constantly train audio models based on the ambient sounds around them, playing back the results live. As the installation progresses, these devices will develop a dynamic understanding of their environment. The artists think of AI as a reproductive process, a way that material produced by humans (and nonhumans) is consumed, commingled, and transformed into something new. In the case of Polyps (and in the case of many AI tools, as they develop across the technology landscape), opting out of this process is difficult, if not impossible. The Polyps interact with the audience by modifying their sonic and luminic behaviours. They upload the recorded material to the cloud and respond with machine learning-generated sounds that increasingly resemble those present in their immediate environment. Additionally, Polyps interact with each other, sharing data, communicating, and reciprocally adapting their behaviours.

The past four years, Marek Poliks and Roberto Alonso Trillo have been collaborating on theory and art-related projects exploring the determining impact of technology on society. Their work focuses on computation (particularly deep learning) and its impact on creative scope and political thought.

# Symbolic Representation of Music in Pitch & Time

This section explores the pivotal contributions of Guido d'Arezzo and Johannes de Muris to the symbolic representation of musical pitch and time. Their innovations laid the groundwork for modern music notation, enabling precise communication of musical ideas across generations.

Stabilising the concept of pitch was crucial for musical development in early Western music. Guido d'Arezzo's solmisation system (ut-re-mi-fa-sol-la), which evolved into today's *solfège*, was instrumental in this process. De Muris' work provided a systematic approach to notating temporal aspects of music, allowing for greater precision in rhythmic patterns. This was a critical development in the *Ars Nova* period (c. 1300 – 1399), fostering the development of more sophisticated musical forms.

Together, these innovations represent a significant leap in music codification, facilitating the algorithmic manipulation of musical elements. They form the basis of Western musical notation, underpinning the evolution of musical thought and practice.

## 2 The Guidonian Hand

The Guidonian Hand was a mnemonic device used in 12th century music teaching, named after its inventor, Guido d'Arezzo (c. 991–after 1033). Guido d'Arezzo was an innovative music theorist whose contributions revolutionised the way music was taught, written, and understood. Born in the town of Arezzo in Italy, Guido joined the Benedictine monastery at a young age, where his passion for music and education flourished. His writings became a fundamental part of mediaeval music education, and his innovations remain essential to modern practice.

### 2.1 *Ut queant laxis & the Guidonian Hand* — Early 16th century

Digital reproduction.
Original size: 15.7 × 10.5 × 3.6 cm.
Bodleian Library MS. Canon. Liturg. 216, Courtesy of Bodleian Libraries, University of Oxford.
Chant with digital animation, looped.
Voice & transcription: Ivo Haun.
Recording & editing: Elam Rotem.
Digital animation designer: Shiro Beta

The Hand's widespread use emerged in the centuries that followed its invention, such as this scaled-up 16th century copy from an Italian Franciscan choir book.

This innovative tool aided singers to locate pitches and understand musical intervals. Each joint and fingertip corresponded to specific notes within the hexachord system (six-note scale), facilitating easier and more accurate melody navigation and memorisation.

The animation of the musical notes on the large scale Hand follows the singing of *Ut queant laxis*, the hymn that inspired d'Arezzo to name the hexachord notes. This display not only highlights Guido d'Arezzo's ingenuity but also underscores the collaborative nature of mediaeval music scholarship. Indeed, the Guidonian Hand marked a significant shift from less structured oral traditions in music education. Its impact extended far beyond its initial use, influencing musical notation and pedagogy for centuries.

The use of this method revolutionised music education, providing a structured system for understanding and teaching musical concepts, allowing for more precise communication of musical ideas and facilitated the development of more complex polyphonic compositions.

### 2.2 *Notations by Guido d'Arezzo* — c. 1025–1026

Digital reproductions: *Micrologus* (MSR-05, folio 91r), *Prologus in antiphonarium* (MSR-05, folio 97r), *Epistola ad Michahelem* (MSR-05, folio 99r). Guido d'Arezzo. Bound with Boethius, *De Musica*. Alexander Turnbull Library, Wellington, New Zealand.

The three digital reproductions present extracts from Guido d'Arezzo's explanations on the development of his innovative system of solmisation, which became today's Western *solfège*. His writings were widely disseminated; the pages presented here come from a later copy known to have been used in the priory of Christ Church Cathedral in Canterbury, England, in the 12th century.

In his *Micrologus de disciplina artis-musicae* of about 1026, Guido d'Arezzo set out the principle of using the first six letters of the alphabet as note names. This manuscript shows how they are associated with words, but also that two voices might move independently. Such a concept of polyphony – the simultaneity of different musical voices – will become fundamental to Western art music through the following millennium.

The *Prologus*, or Prologue page, stems from Guido d'Arezzo's *Lost Antiphoner* (1025) – a book of chants notated using the new system he describes here. Hitherto, chants had been notated on three or four lines marking notes only the lines themselves and with no common pitch reference. To standardise notation, make it more efficient to understand and to establish common references of pitch, d'Arezzo proposed to use the space as well as the lines of four-line staves. The pitches represented by the lines are thus a third apart (e g b d), and likewise the spaces. In addition, a symbol at the beginning of the line – our modern *clef* – indicates the reference pitch. With the addition of a fifth line a century later, this system remains in use today. Guido d'Arezzo described it thus:

"The sounds, then, are so arranged that each sound, however often it may be repeated in a melody, is found always in its own row. And in order that you may better distinguish these rows, lines are drawn close together, and some rows of sounds occur on the lines themselves, others in the intervening intervals or spaces. Then the sounds on one line or in one space all sound alike. And in order that you may also understand to which lines or spaces each sound belongs, certain letters of the monochord are written at the beginning of the lines or spaces and the lines are also gone over in colours, thereby indicating that in the whole antiphoner and in every melody those lines or spaces which have one and the same letter or colour, however many they may be, sound alike throughout, as though all were on one line." *

The final manuscript page on display, a letter written by Guido d'Arezzo to his friend Brother Michael (*Epistola ad Michahelem*), describes a method he has developed to accelerate the teaching of new chants to choirboys. His secret was the chant *Ut queant laxis* (a hymn to St John the Baptist), in which each phrase begins one step higher (*Ut..., re(sonare)..., mi(ra)..., fa(muli)..., sol(ve)..., la(bii)....).* We retain this today, a thousand years later, in the do-re-mi of Western *solfège*.

*Translation from Oliver Strunk (1965), Source Readings in Music History. vol.1, 118–119.

## 2.3 *The Hexachord Notes* 2024

Interactive app with chant recording.
Voice: Ivo Haun.
Recording & editing: Elam Rotem.
Animation: Shiro Beta.
Image of the Guidonian Hand: Bodleian Library MS. Canon. Liturg. 216, Courtesy of Bodleian Libraries, University of Oxford.

Guido d'Arezzo wrote all 22 notes of the hexachord on every finger joint and tip, in a spiral manner. The 22nd was in fact placed at the back of the middle finger. The first note, *ut,* reads on the thumb's tip. The notes then continue down the finger and along the hand.

## 3 *Libellus cantus mensurabilis* c. 1340

Digital reproduction from original manuscript. MS 410, Folio 37v/38r, The Parker Library, Corpus Christi College, Cambridge.

## Johannes de Muris

was a French mathematician, astronomer, and music theorist (1290–c. 1355).

De Muris was instrumental in shaping the *Ars Nova* movement in 14th century music. The manuscript on display stems from his Book of measured song, where time is being measured. It shows the *Ars Nova* proposal of a rhythm notation, very recognisable and still in conventional use. Within a proportional system based on 'perfect' (triple) and 'imperfect' (duple) relationships, we see de Muris setting out his notation using 'lungo', 'breve', 'semibreve' (our modern whole note) and 'minim' (our half note), the shortest value.

# Polyphony

Polyphony reached its heights of complexity during the late Middle Ages and the Renaissance. The objects here explore the development of early musical polyphony and the algorithmic thinking and tools that are enabled by it. Polyphony and counterpoint are based on the invention of a complex ruleset that describes how notes could be combined and ensure the treatment of dissonance, and later, harmony. Composers like Baude Cordier and Josquin des Prez or theorists like Pedro Cerone pushed the boundaries of musical composition, employing advanced techniques to weave independent voices into harmonious structures. This period saw the introduction of innovative tools and methods, such as the polyphony slate for calculating musical intervals and the algorithmic processes behind works like des Prez' *Missa Di dadi.* Athanasius Kircher's *Arca Musarithmica* epitomises the algorithmic approach to music. This ingenious device mechanised composition, allowing users to create polyphonic music by selecting from pre-composed segments, reflecting early computational thinking in music.

Polyphonic music reveals a fascinating interplay between creativity, beauty, and mathematical symmetries. Together, these artefacts highlight the evolution of polyphonic music and counterpoint, showcasing how composers utilised both artistic intuition and scientific methodologies to create complex, multi-voiced compositions.

## 4 *Belle, Bonne, Sage – Tout par compas* c. 1400

Digital reproduction from the original manuscript, *Codex Chantilly*. Courtesy of Château de Chantilly, Musée Condé, manuscrit 564, f. 11v. Bibliothèque du Château de Chantilly.
Music: *Belle, Bonne, Sage*, 2:22 mins. *Tout par compas*, 3:54 mins.

### Baude Cordier

was a French composer and poet of the late mediaeval period (c. 1380 – c. 1440).

The double-page manuscript on display showcases two of Baude Cordier's most striking works. On the left, the love song *Belle, Bonne, Sage*, dedicated to a noble lady. Known as a rondeau, a lyrical style in French poetry, the author praises the beloved's beauty, goodness, and wisdom, qualities that were highly esteemed in the courtly culture of the mediaeval period. The combination of poetic lyrics, complex musical structure, and symbolic notation exemplifies the sophistication and elegance of the time's *Ars Subtilior* style. What sets this manuscript apart is its unique and elaborate heart-shaped notation, a visual representation that complements the romantic theme of the piece. Each note is meticulously placed within the contours of the heart, making the manuscript not only a musical score but also a work of visual art. This graphical complexity mirrors the intricacy of musical thought, made possible by the new symbolic notation. For example, it allows a composer to imagine subdividing the beat by 2 and 3 (and their multiples) at the same time, as happens in the piece on the right, *Tout par compas suy compose*. We can see anticipation of the computer-assisted practices of recent decades, as in the complex scores of composers such as Brian Ferneyhough. This manuscript is a rare and precious artefact that highlights Baude Cordier's exceptional talent and creativity, and provides insight into the rich artistic and cultural environment of the late mediaeval period.

## 5 *Polyphony Calculating Slate* c. 15th century

Slate with musical notation.
Clay, 12.3 × 5.9 × 0.9 cm
Courtesy of the City of Ghent, Urban Archaeology and Heritage Conservation Service.

This slate, found in 1993 during excavations on the Sint-Baafsplein in Ghent, served as an erasable tablet for writing music, akin to a reusable notebook. It features a tenor melody on a five-line stave, likely a section of a chant or a *cantus firmus* (a fixed, pre-existing ecclesiastical chant used as the foundation for new compositions).

In the 16th century, composers were adept at creating intricate polyphonic works, such as motets and masses, without the use of a score. Much of the composition was performed mentally with minimal notation, and the final work was presented in part-books, each singer seeing only their own line. This method involved taking a *cantus firmus* section or creating a new musical phrase (a 'point') and imagining compatible phrases ('counterpoint'). Renaissance polyphony, which peaked with composers like Josquin des Prez and Palestrina, employed formal processes such as imitation, transposition, inversion, and the diminution and augmentation of time.

Without an overall view of the entire work, composers had to mentally envision the sequences of notes and rhythms and the processes they would undergo to create a complete form. This could be seen as an algorithmic process. Composers used erasable tablets like this slate or wax tablets ('cartella') to notate, examine, and teach these musical materials and their combinations. This slate likely served this educational and compositional purpose in its last use.

## 6 *Enigma del Espejo* 1613

In *El melopeo y maestro*.
Published in Naples.
Book: 33 × 23 × 10 cm.
Orpheus Instituut, Ghent.

### Pedro Cerone

was an Italian priest, music theorist and composer working at the Spanish-speaking court of Naples and later in Spain (1566–1625).

*El melopeo y maestro* (The Songmaker and Master) is Cerone's comprehensive treatise covering a wide range of topics related to music theory, composition, performance and liturgical music of the period. Spanning over 1,000 pages, the treatise provides, among other subjects, valuable insight into the theoretical underpinnings of Renaissance polyphony and the practices of sacred vocal music in use at Spanish and Italian churches and courts in the early 1600s.

In the final part of his treatise, Cerone presents a compendium of musical riddles, known generally as 'enigmatic' or 'puzzle' canons. They range from direct imitation to more complex multi-section, multi-part motets. Cerone gives playful clues as to how the reader might construct an entire movement. This requires both knowledge of the musical style and a process of algorithmic play to imagine how the piece might be completed. In many cases, he presents the riddles in inventive graphical forms – as a cross, a hand throwing dice, a pair of snakes and even an elephant. In *Enigma del espejo*, or Riddle of the Mirror, the latter is the clue. Indeed, the page displayed requires the simultaneous solution of two mirror canons – that is, where several voices sing the same music at different times, but some of them read their part in reverse. Reading a musical phrase backwards ('retrograde') is a conventional part of the polyphonic technical repertoire. Here, the solver must look at the page in a mirror to see how the four-voice piece can work. Cerone gives the following clue for his puzzle:

"First you will sing as you see her;
Second (and with quick feet)
To the trusty mirror, which wishes to show you
Where, when and how you should sing.
And the key to this new game
Will be in C, in the low bass".

## 7 *Je Missa Di dadi* c. 1480

In *Missarum Josquin Liber Tertius*.
Published by Ottavino Petrucci, Venice, 1514.
Digital reproduction.
Original size: 16 × 22.5 cm.
SA.77.C.20 / Liber III / Tenor, fol. 28v–29r. Courtesy of ÖNB Vienna.

### Josquin des Prez

was a Franco-Flemish composer of the Renaissance (c. 1450–1521).

In *Missa Di dadi*, Josquin des Prez turns to well-known material: the melody *N'aray je jamais mieulx* ( Shall I never fare better than I do) by the English composer Robert Morton (c. 1430–1479). Des Prez appears to use rolls of the dice to determine the time relationships between Morton's melody as the *cantus firmus* in the tenor (shown here) and the other three voices. The tenor singer has to calibrate the speed of his part according to this ratio to make it fit. Thus in the initial *Kyrie* (an important sung prayer of Christian liturgy), he must sing at half the speed of the others (2:1).

Theories abound as to the significance of the dice; a reference to the gambling at the court of the Sforza in Milan where des Prez worked, or perhaps something more numerological. Interestingly, des Prez shares the constraints he sets himself for his work, and that he does so in a form of abstraction, a quasi-formalist action lost to the listener with no indication or sight of the music. Whether or not Josquin des Prez actually used dice in his compositional process, this work has had a significance for composers in the 20th century as they dealt with operations of chance and the co-existence of multiple possible paths.

## 8 *Missa L'homme armé super voces musicales – Agnus II* 1502, 2024

Originally published by Ottavino Petrucci, 1502. Annotated score by Jonathan Impett.

### Josquin des Prez

was a Franco-Flemish composer of the Renaissance (c. 1450–1521).

Known for his technical virtuosity, Josquin des Prez gained a reputation as the master of the polyphonic style of the Renaissance. He introduced a practice of imitation of small melodic motifs, creating a wider field for development than the earlier focus on longer melodic lines.

Instead of taking a *cantus firmus* (a fixed and pre-existing passage of ecclesiastical chant used as the basis for a new composition) from the body of a Gregorian chant, composers sometimes took well-known melodies that afforded similar contrapuntal treatment. *L'homme armé* is one such melody, used as the basis of masses by many composers, from Franco-Flemish composer Busnois (possibly the melody's originator) in the later 15th century to the monumental 12-part mass of Italian composer Carissimi in the mid 17th century.

The second setting of the text *Agnus Dei* from Josquin des Prez' *Missa L'homme armé super voces musicales* demonstrates clearly the use of a single melody subject to the essential processes of such contrapuntal polyphony, in a tight construction of three parts. The melody appears in its slowest form in the central alto voice. Around it, the bass and soprano both present exactly the same material but shifted five steps down / four steps up. The bass moves at twice the speed of the alto, the soprano at one third, all the while conforming to the strict rules of polyphonic motion and harmonic alignment. This strict construction is known as a 'mensuration canon', and is described by Pietro Cerone (display n°6).

# 9 *Six Ways to Represent Music* 2024

Music: Franz Schubert, *4 Impromptus, D. 899, Op. 90 No. 3 in G-flat major*, 06:04 mins. Digital and Cognitive Musicology Laboratory (DCML), EPFL.

## EPFL-DCML

While music is most commonly associated with sound, it exists in multiple mediums, each with its own interaction modalities; from manuscripts to scores, to audio recordings, computer-readable score representations, digitally engraved scores, or even computer programs that describe and recreate musical pieces. Six of such forms of music description are displayed in this installation.

Scores (1) or manuscripts (2) do not capture how a piece of music sounds but represent either actions for performers or abstract musical effects to be interpreted in sound. The notation of the piece in question begins with the indication “No. III” on the left margin of the sheet and is preceded by the ending of the previous Impromptu in Schubert’s cycle. When musical scores are represented digitally (3), this information is translated into a computer-readable format.

The “piano roll” (4) represents note events in time as a two-dimensional “canvas” of time and pitch. The roll represents each note with a perforated rectangle that indicates its pitch (height), onset time and duration. Piano rolls were originally used as a recorded performance medium, and are nowadays adopted in computational models of music analysis and composition.

Audio representations of music (5), such as waveforms or spectrograms, enable analysis and manipulation with recording and audio technologies. Finally, a piece may be (re-)generated by an algorithm (6) based on given rules, applied either deterministically or probabilistically, and executed by a human or a machine.

This exhibit highlights the technological advancements and cultural shifts that have shaped how music is written, manipulated, and understood over centuries. From ancient notation to modern digital formats, illustrating the ongoing intersection of music and technology, providing new tools and perspectives for musicians and composers.

# 10 Athanasius Kircher

Athanasius Kircher (1602–1680) was a German Jesuit scholar and polymath whose work spanned fields such as geology, medicine, and music theory. Renowned for synthesising knowledge from diverse domains, Kircher is a key figure in the history of science and music. His major work, *Musurgia Universalis* (1650), covers a broad range of musical topics, from the mathematical foundations of music to the history of musical instruments. Kircher applied algorithmic and combinatorial methods to music theory, creating devices like the *Arca Musarithmica*, an early music-composing machine that demonstrated the potential of algorithmic composition, a precursor to modern computational music.

Kircher’s fascination with acoustics and the physical properties of sound led to detailed studies on echos, resonance, and the design of musical instruments. He believed in a universal harmony that connected music with cosmic and divine order, blending mystical and scientific perspectives. Kircher’s work provided a comprehensive view of music as both an art and a science, influencing future generations of scholars and composers. His contributions highlight the early intersections of technology, science, and the arts, setting the stage for future explorations in algorithmic and computational music.

## 10.1 *Arca Musarithmica* 1650

Hand-drawn illustration. Digital reproduction. Published in *Musurgia Universalis* by A. Kircher. Sp Coll Ferguson Af-x.10, by permission of the University of Glasgow Archives and Special Collections.

The *Arca Musarithmica*, a music arithmetic box, described in Kircher’s *Musurgia Universalis* (display 10.3), is an early computational device for automated music composition. Kircher’s own illustration of his *Arca Musarithmica* can be admired here. On the lid and front are inscribed a full taxonomy of scales, modes and their characteristics, as well as illustrations of ancient instruments – those of Greece and Egypt, as understood by Kircher. Inside the chest are the elements that can be removed and used in combination. Each is marked with its poetic metre and number of syllables, the scale it uses, and whether it is ‘florid’ or simple. A user can then combine these elements to produce an appropriate four-part vocal score for their chosen text.

This “box for musical calculation” allowed even those without musical training to compose complex music by following Kircher’s rules. It contained tables and slats with prearranged permutations of numbers and rhythms, which users combined to generate four-part compositions in various styles.

Kircher claimed the device could produce music that professionals would recognise as correct and expressive. His Jesuit contemporaries spread the *Arca Musarithmica*’s influence globally, with evidence of its use and adaptations found as far as Manila and Mexico City. Nowadays, only three very fragile copies exist in Europe and one in Mexico, and it is impossible to display any of them here.

The *Arca Musarithmica* represents a fascinating intersection of music theory, combinatorial mathematics, and early computational ideas. It highlights the innovative spirit of the 17th century and Kircher’s quest to codify the mathematical order underlying musical composition.

## 10.2 *Neue Hall- und Thon-Kunst* 1673

Book, 35.5×23×4.5 cm. Orpheus Instituut, Ghent.

Kircher’s *Neue Hall- und Thon-Kunst* (New Art of Acoustics and Sound) is an exploration of the acoustic properties and technologies of sound. Kircher delves into the mechanics of sound production and propagation, bridging the gap between theoretical acoustics and practical musical applications.

*Neue Hall- und Thon-Kunst* presents detailed analyses and descriptions of musical instruments, architectural acoustics, and sound amplification techniques. His investigations include discussions on the design of spaces for optimal sound diffusion and the construction of devices that manipulate sound waves. These studies are complemented by diagrams and illustrations, offering insights into the practical implementation of his theories.

Kircher’s work stands out for its innovative approach to understanding sound, combining empirical observations with theoretical constructs. This text not only reflects the scientific curiosity of the Baroque period but also serves as a precursor to modern acoustic science, influencing subsequent developments in music technology and the study of sound.

## 10.3 *Musurgia Universalis*

1650

Digital reproductions of illustrated plates. Sp Coll Ferguson Af-x.10, by permission of the University of Glasgow Archives and Special Collections.

Kircher's *Musurgia Universalis*, or Universal Music, is one of the most comprehensive works on 17th century music theory and practice, known for its inventive illustrations and diagrams. Three such illustrations are on display.

The first one, 'The Harmony of the Birth of the World,' depicts a cosmic organ with six registers corresponding to the days of creation. Below the keyboard the inscription reads, "Thus plays the wisdom of the everlasting God in the earthly orb." This reflects Kircher's belief in the fundamental connection between music and the universe's essence, an idea rooted in ancient Greek music theory and further developed in the 'harmony of the spheres' by cosmologist-astronomers like Johannes Kepler.

The second illustrates an automated organ with a rotating barrel and protruding pins to play the keys. On the left, humanoid automata work at an anvil, referencing Pythagoras' theory of intervals. On the right, humans dance to the universe's music, with the inscription, "God loves the odd number. So all sing praises to God with a triple song."

The third and last illustration features another organ mechanism (considered the king of instruments): a *hydraulis* or water-organ, powered by the flow of water, generating the music of animals and gods. This illustrates how music connects the material and spiritual worlds in precise technical ways.

*Musurgia Universalis* is a testament to Kircher's encyclopaedic knowledge and his commitment to synthesising diverse fields of study. It remains a pivotal reference for scholars of music history and theory, offering a window into the intellectual and artistic currents of the 17th century.

# Musical Geometries

This part of the exhibition brings together different ways to conceptualise spaces of pitch relations in music: it displays the *Tonnetz* ("tonal network") as first established by Leonhard Euler in his treatise on music as well as a later different version of the same idea by Otakar Hostinsky. It also shows the first historical account of the circle of fifths (intervals between two notes, separated by 5 degrees), which is still one of the most central ways to conceptualise the relationships between pitches, chords and keys. In addition, this section highlights two less famous geometries; the *12-part Colour-Sound Circle* by J.M. Hauer, as well as a different tonal circle drawn by John Coltrane which demonstrates the enduring application of this concept. The section concludes with four animations of musical analyses based on current research of the EPFL's Digital and Cognitive Musicology Laboratory involving the *Tonnetz*, hierarchical harmonic trees, networks of tone relations, and a 3D cloud of relations between musical segments.

## 11 *Musikalisches Würfelspiel* 1792, 2024

Software development: Alexander M. Aguilar. Project leadership: Martin Rohrmeier, Ioannis Rammos.

# W. A. Mozart [?]

Probably composed by Mozart, the *Musikalisches Würfelspiel* (Musical Dice Game) is an example of early algorithmic composition and published in various versions since 1792. It allows players to create a unique minuet (musical dance form stemming from the Baroque era) by rolling two dice and selecting the corresponding fragments of music from among 176 precomposed measures, which are provided in a numbered grid. Each measure can thus be preceded or succeeded by alternative materials, resulting in a virtually endless number of possible compositions. The Dice Game is not only a delightful musical pastime but also an early example of generative music, demonstrating its creator's playful creativity. It involves two tables of 16 rows each. The player rolls a pair of dice to select a measure from each table. Interlocking these selections results in a coherent and stylistically consistent minuet. This historical musical game reflects the Enlightenment-era fascination with probability and combinatorics, blending art and mathematics in a manner that prefigures modern algorithmic and computer-generated music.

The interactive app in this exhibit is a digital reincarnation of the Dice Game.

## 12 *Tentamen novae theoriae musicae* 1739

Book, 25,5 × 19,5 × 3 cm. On loan from ETH-Bibliothek Zürich, Rare Books, Rar 5162.

# Leonhard Euler

was a Swiss mathematician and physicist (1707–1783).

Leonhard Euler is best known for his ground-breaking work, including integral calculus, graph theory, and number theory; Euler's identity, $e^{i\pi} + 1 = 0$, is sometimes called the most beautiful formula in mathematics. Perhaps because of this aesthetic sensibility, Euler had a little-known lifelong preoccupation with music and applied mathematical principles to the study of music theory.

In 1739, Euler wrote *Tentamen novae theoriae musicae* (Attempt at a New Theory of Music), one of his few works devoted specifically to music. In his treatise, Euler approached musical concepts like the subdivisions of octaves into fractional parts from a mathematical perspective, introducing ideas like binary logarithms to numerically describe these relationships. This exhibit displays one central contribution in this treatise that is still relevant for music theory and musical formalisms today; the *Tonnetz.* Euler's 'tone network' is grounded in a theory of 'just intonation' and provides a means of representing relations between various tones in two-dimensional geometric fashion, as a space comprised of musical intervals. In particular, the space is constructed from the intervals of the fifth and the third.

While his mathematical approach was sometimes criticised as too technical for musicians, Euler saw potential in eventually incorporating musical theory as a formal part of mathematics. His pioneering work applying numerical concepts to music theory foreshadowed some later developments in the field.

## 13 *Circle of Fifths* 1679

Digital reproduction, copy of the original facsimile. The New York Public Library.

# Nikolay Diletsky

was an Eastern European composer, music theorist, and choral conductor (c. 1630–c. 1680).

Diletsky's Circle of Fifths represents one of the earliest known accounts of this now-essential theoretical structure for tonal music. It was first introduced in his 1679 treatise *Grammatika Musikiyskago Peniya* (Grammar of Musical Singing). The Circle of Fifths is a visual representation that illustrates the relationship between different pitches, chords or keys in Western music, arranging them in a cyclical order of 12 steps of fifths. The 'fifth' constitutes the main relationship of what is called authentic or plagal progressions (descending or ascending fifths respectively), which are fundamental throughout the history of Western tonal music up until the present day.

Diletsky's innovative use of the Circle of Fifths was revolutionary for its time, significantly influencing the development of music theory in Eastern Europe, particularly in Russia and Ukraine. It offered a systematic approach to understanding musical tonality. His diagram not only mapped out the major keys but also integrated minor keys, providing a comprehensive view of the tonal landscape.

## 14 *Die Lehre von den musikalischen Klängen* 1879

Digital reproduction from the New York Public Library. Originally published by H. Dominicus, Prague, 1879.

# Otakar Hostinsky

was a renowned Czech musicologist, theorist, and Professor of musical aesthetics (1847–1910).

*Die Lehre von den musikalischen Klängen* (The Doctrine of Musical Sonorities) is a foundational text in the fields of music theory and harmony. Hostinsky's treatise explores the properties of tones and hearing, the harmonic series, musical intervals, consonance and dissonance, melody, and leads to a proposed doctrine of harmony (*Akkordlehre*).

The exhibit displays Hostinsky's version of a musical network structure connecting note names, which allows one to trace the harmonic movement in musical compositions as a path along the network. The structure is similar to Euler's *Tonnetz*, while its arrangement is hexagonal.

The publication of this work in the late 19th century marked an important development in the study of music, influencing subsequent research in both music theory and acoustics. *Die Lehre von den musikalischen Klängen* bridges the gap between the technical and artistic aspects of music. Hostinsky's insights into the scientific foundations of musical sound laid the groundwork for modern acoustical studies and continue to inform both theoretical and practical explorations in music. This work reflects Hostinsky's ability to synthesise knowledge across disciplines, marking him as a pivotal figure in the development of music theory and acoustics.

## 15 *12-part Colour-Sound Circle* 1919

Facsimile, pasted coloured paper, ink, pencil on paper, 34 × 21 cm. Courtesy of mumok – Museum moderner Kunst Stiftung Ludwig Wien, Sammlung Dieter und Gertraud Bogner im mumok.

## Josef Matthias Hauer

was an Austrian composer and music theorist (1883–1959).

Hauer's *12-part Colour-Sound Circle* is a pioneering exploration of the synesthetic relationships between music and the visual arts. Synaesthesia is a neurological phenomenon in which the brain mixes two or more senses. Inspired by the works of painter and art educator Johannes Itten, Hauer assigned specific colours to the keys within the circle of fifths and fourths, representing the chromatic scale's twelve pitches. It visually represents musical relationships, serving as both a compositional tool and a reflection of Hauer's philosophical ideas about music's connections to other sensory experiences.

Hauer's approach to twelve-tone music emphasised spiritual and intuitive aspects, differing from contemporaries like Arnold Schönberg. He developed a unique eight-line stave notation system for his twelve-tone 'modes', enabling new ways of manipulating musical material within his harmonic world.

This artefact provides insight into Hauer's theoretical framework and his contributions to modern music theory. It highlights his perspective on the interplay between artistic and sensory modalities, underscoring his belief in music as a universal language. The *12-part Colour-Sound Circle* remains an important resource for understanding Hauer's innovative approach to music composition, his efforts to synthesise auditory and visual art, and his contributions to the fields of music theory and synaesthesia.

## 16 *Coltrane's Circle* 1960s

Digital copy of the diagram from Yusef Lateef, in *Repository of Scales and Melodic Patterns*, 1981. Jamey Aebersold Jazz.

## John Coltrane

was an American jazz saxophonist and composer (1926–1967).

Known for his pioneering work in Bebop jazz and for leading the way in the development of new improvised music, John Coltrane's innovative techniques and compositions have left an indelible mark on the world of music. His mastery of the saxophone, coupled with his relentless pursuit of new musical ideas, made him a central figure in the evolution of jazz.

Coltrane's Circle is a hand-drawn conceptual diagram of tonal relations between notes. It consists of two cyclic rows of notes juxtaposing the two different six-note whole-tone cycles (evenly-spaced scales) in music, each repeated five times. The star shape in the centre connects the five occurrences of the starting note C. The drawing further highlights twelve groups of three semitones (such as B-C-C# at the top). When alternating between the two whole-tone scales the middle notes of each of the 3-tone clusters establish a cycle of fifths. Further indications underpin major-third relations within each of the whole-tone segments, as well as augmented triads that are established in these cells. His classic tune *Giant Steps* – an established challenge to virtuosity in jazz improvisation – is built on such patterns. This circle exposes Coltrane's deep understanding of the relationships and harmony within the music he was creating. Coltrane gave the drawing to saxophonist and jazz educator Yusef Lateef, who included it in his seminal text for improvisers.

## 17 *Four Perspectives on Structure in Music* 2024

Animated visualisations, 2–3 mins each, looped. Digital and Cognitive Musicology Lab (DCML), EFPL. Project leader: Martin Rohrmeier. Programmers: Kalan Walmsley, Ioannis Rammos, Robert Lieck

## EPFL-DCML

In the course of music history, the structural organisation of music has changed in diverse ways. This exhibit invites the visitor to experience four different kinds of musical structure unfolding while listening. Altogether, the four exhibits illustrate different types of complexity and relations that are encountered in the Western musical tradition and collectively generate an enormous range of compositional effects, which a listener may discover in music.

### 17.1 *The Unfolding Tonnetz*

Dataset: Francesco Foscarin *et al.*, "ASAP: A Dataset of Aligned Scores and Performances for Piano Transcription.", 2020. Curtis Hawthorne *et al.*, "Enabling Factorized Piano Music Modeling and Generation with the MAESTRO Dataset.", 2019.

Music: Fryderyk Chopin , *Etude Op. 25 No. 5 in E minor*, 03:15 mins. Franz Liszt, *Concert Etude S. 145 No. 2* ("Gnomenreigen"), 02:45 mins.

The formulation of the *Tonnetz* (tone network) by Leonhard Euler (1707–1783) and Otakar Hostinsky (1847–1910) was a major milestone in music theory (displays n°12 and n°14). It provided a means of representing relations between various tones of a musical piece in geometric fashion, as motions within a 'space'. This animation illustrates the tonal relations of an example piece within the space of the *Tonnetz*, highlighting the fundamental role of certain intervals: the fifth, the major third and the minor third.

### 17.2 *The Tonal Cloud*

Music: Johann Sebastian Bach, *Prelude No. 6 in D minor*, BWV 851, 1:24 mins. *Prelude No. 13 in F-Sharp major*, BWV 857, 1:23 mins.

Segments of music can be compared in terms of their pitch contents. When very large numbers of segments of idiomatic Western music are collected into a single dataset and arranged within a three-dimensional space by a machine learning algorithm, so that similar segments are close to each other, the shape of a torus emerges. Among other insights, this result closely reflects properties of Euler's and Hostinsky's *Tonnetz* (see displays n°12 and n°14).

## 17.3 *Live Visualisation of Syntactic Tree Structures*

Music: Duke Ellington, *Satin Doll*, 1:00 min excerpt.
Johann Sebastian Bach, *Prelude No. 1 in C major*, BWV 846, 02:20 mins.

As with words in natural language, chords are also organised in hierarchical order and exhibit grammatical relationships that may unfold on different timescales. The trees in this video illustrate syntactic dependency relations not only between consecutive chords (bottom), but also between chords potentially seconds or minutes apart (top).

## 17.4 *3D Visualisation of Hierarchical Tone-by-Tone Relations*

Music: Johann Sebastian Bach, *Prelude in F minor*, BWV 857, 02:10 mins excerpt.

Typically, notes within a piece of Western tonal music are related in a variety of ways: they may be, for instance, members of an overarching melodic line, or neighbours in the scale, or consonant with each other. Additionally, some notes are structurally more important than others. This video visually renders the network of such relations while the piece is played back. Different layers indicate different levels of structural importance and provide ‘summaries’ of the piece on different timescales.

# Non-Western Music

Algorithmic and computational thinking is a fundamental aspect of human intelligence exhibited across musical cultures. The installations here highlight the rich tradition of algorithmic thinking in non-Western music, showcasing the intricate structures of Indonesian Gamelan, Indian rāga, and Central African music. Gamelan music, with its layered rhythms and interlocking cyclical patterns, demonstrates a precise and communal algorithmic process. Indian rāga, with its intricate rules for melodic development and scalar expansion, reflects a deeply algorithmic framework guiding both improvisation and composition. Central African music, known for its polyrhythms and interlocking patterns, illustrates sophisticated geometry and mathematical principles in its rhythmic structures. Through these examples, the exhibition reveals the universal nature of algorithmic and computational thinking in music, transcending cultural boundaries and enriching the global musical landscape.

# 18 Gamelan Music

## 18.1 *Gamelan*

Selunding gamelan element (East Bali, Indonesia). Metallophone with playing sticks (1983): iron, jack tree wood, buffalo leather. 29×59.5×49 cm. ETHMU 048260, The Museum of Ethnography Geneva (MEG). Bali, Indonesia
Music: Ladrang "Prabu Mataram", 7:04 mins.

Indonesia is home to around a hundred different types of percussion ensemble known as gamelan. A collective instrument made up of elements as interdependent as the keys on a piano, it is essentially made up of chimes (gongs) and/or keyboards with blades, playable only collectively, produced simultaneously (from the same bronze, iron or bamboo) and tuned only to each other.

The metallophone on display here is part of a Selunding, the oldest type of gamelan in Bali, which is a large blade keyboard made up of 8 modules assembled in various ways to create different arrangements of the same musical pieces by varying the number of musicians per module.

The Ladrang form of royal Javanese music, Prabu Mataram, is representative of the hierarchical, algorithmic musical structure specific to gamelans, inspired by Hindu-Buddhist Tantric cosmology. The symmetrical musical wheel (*gongan*) is repeated by the gamelan alone (during the entrance of the sovereign). Then (at 0:40 mins) the ratio changes, the same *gongan* is stretched considerably, allowing the addition of songs, melodic improvisations by individual instruments, clapping and rhythmic shouts.

The metrical basis, inherited from the ritual ringing of gong chimes, consists of sounded wheels of time (*kalacakra*): cycles (*gongan*) initiated and completed by the striking of the lowest sound (called a gong regardless of the object emitting it). The various subdivisions of the *gongan* are each sounded by a specific timbre and, originally, by a specific note. The different forms are defined by the metre of their *gongan*. For action and processions, asymmetrical musical wheels give the impression of moving forward. Through changes in ratios, the expansion of the cycles serves aesthetic purposes, while their contraction is necessary for purification rites and fights.

## 18.2 *Digital Gamelan*

Video. Under the direction of Catherine Basset, based on the interactive app *Le Gamelan numérique*.
Educational coordinator: Gilles Delebarre, Cité de la Musique
Scientific director: Catherine Basset
Coordination: Marie-Hélène Serra
Interactive design and production: Olivier Koechlin


## La Philharmonie de Paris & Catherine Basset

The video illustrates an element of the research carried out by ethnomusicologist Catherine Basset. She has highlighted the fundamental algorithmic structure of Gamelan music and its link to the Hindu-Buddhist mandala, *cakra* (cogwheel), *kalacakra* (Wheel of Time) and *padma* (lotus), thanks to her invention of a concentric, mathematically exact graphical musical notation: set to sound, it actually plays the music.

The Javanese Ladrang form is particularly representative of the basic fractal system, known as Dhongdhing, as well as of the changing ratios between the timbre metric wheel and the melodic parts, which, here limited to ratios (*irama*) 1 and ×2, can range from 1/2 to ×16.

In supreme position, the timbre and the gong note dominate a hierarchy of tessituras in which the algorithmic principle generates fractals of a tree-like "b-A-b-" pattern.

The video is a demonstration of a small part of the *Digital Gamelan* (formerly the *Mechanical Gamelan*). The App offers, for a Sundanese form (two Javanese forms and a Balinese form divided into Baris and Gilak by the 8-track limitation), an interactive game on each of the three gamelans as well as on the tablature notation, which allows one to compose. The concentric notations reveal the permanent form, while a change of musical piece only modifies the colours of the musical notes.

To find out more, try out the digital Gamelan and consult the supplement to Catherine Basset's book at the bottom of the home page.

# 19 *Polyrhythms in Central African Music*

Polyrhythmic music, 21:46 mins, looped. Excerpts from *Ligeti/Reich. African Rhythms*.

Central African music encompasses a rich diversity of musical traditions from countries such as the Democratic Republic of the Congo, Cameroon, and the Central African Republic. This music is characterised by its intricate rhythmic patterns, polyphony, and the use of various traditional instruments, including drums, thumb pianos (like the mbira), and stringed instruments.

The sound installation here allows an immersion in the sounds of Central African music. Their algorithmic nature manifests through complex rhythmic cycles and interlocking patterns, often governed by a set of rules and formulas that guide the performers. A particular feature lies in the use of polyrhythms (instrumental or vocal), where multiple rhythmic patterns are played simultaneously with different periodicities or starting points. This creates a dense and layered sound that is both dynamic and highly organised. For example, in the music of the Aka (or BaAka) people, different drumming patterns are layered in a way that each pattern interlocks with others, creating a composite rhythm that is more complex than the sum of its parts. Also, the concept of hocketing, where two or more voices or instruments alternately play notes to create a continuous stream of sound, is prevalent in Central African music.

This intricate and systematic approach to music-making showcases the deep cultural and mathematical understanding inherent in Central African musical traditions. These communities have developed complex systems that continue to influence contemporary music practices worldwide and have inspired many composers such as György Ligeti (display n°29.2) or Steve Reich.

20

# *Scalar Expansion in North Indian Classical Music*

2024

Digital animation: Kalan Walmsley
Music: *Alap of rāga Multānī*, performed by Dharambir Singh.


## Martin Rohrmeier and Richard Widdess

Martin Rohrmeier is a professor of Digital Musicology at EPFL.

Richard Widdess is emeritus professor of Musicology at the School of Oriental and African Studies, University of London.


Indian classical music's two major distinct traditions, North and South Indian, both exhibit algorithmic principles in their structured melodic systems. The North Indian tradition revolves around *rāgas*; intricate melodic frameworks with strict rules governing note selections, progressions, and emotional expressions.

A *rāga* has a defined array of ascending and descending scales (*āroh* and *avāroh*), principal and secondary notes (*vadi* and *samvadi*), and characteristic phrases (*pakad*). Performances unfold through sections like *ālāp, joṛ,* or *jhala*, allowing for improvisation within the *rāga's* constraints.

The wall projection illustrates how North Indian *rāgas* organise their melodic material in the *alap* part based on algorithmic principles. Such *ālāp* parts are organised according to a Scalar Expansion Principle. This algorithm iteratively expands an initial short phrase into gradually longer and more intricate phrases, covering the entire scale range. The purpose is to progressively reveal the *rāga's* scale and properties to the listener before the piece proceeds to the *joṛ* section. This exhibit demonstrates the stepwise phrase expansion process, accompanied by a playback example. Numbers represent the different scale degrees (1 to 7) within the specific *rāga's* scale.

This animation exemplifies how traditional music can embody algorithmic principles.

# Automata

This section of the exhibition showcases the fascinating world of musical automata, explaining the historical efforts to use technology to replicate and enhance human musical performance. Automata illustrate ways to replace the human performer in music. They demonstrate how early inventors harnessed mechanical ingenuity to create self-playing instruments. These automata not only served as marvels of craftsmanship and engineering but also as precursors to modern algorithmic music technologies, embodying an early form of computational and systematic thinking in their programmed sequences and mechanical precision. The selected artefacts on display in this exhibition reveal the enduring quest to blend artistry and technology, transforming the way music is created and experienced.

## 21 *Persian Automaton* c. 12th century

Digital reproduction from original manuscript.
National Museum of Asian Art, Smithsonian Institution, Freer Collection, Purchase – Charles Lang Freer Endowment, F1930.73.

This illustration depicts an early example of a Persian musical automaton. Originating from the rich cultural heritage of the Islamic Golden Age, this automaton reflects the period's advanced understanding of engineering, clockwork, and artistry.

The artwork showcases a sophisticated mechanical device designed to entertain and amaze with its automated musical performance, capturing a scene of vibrant human figures and intricate machinery. The automaton is powered by water and gravity, a common driving force in many early automata, employing a series of gears, levers, and waterwheels to produce music. It features a group of musicians, each playing a different instrument, all coordinated by the hidden mechanisms below. The use of water to drive mechanical music devices was a hallmark of medieval Islamic engineering, showcasing its ingenuity and expertise in creating complex and engaging machines.

Such automata were often featured in royal courts and affluent households, symbolising wealth and intellectual prowess. They served both as luxurious entertainment and as demonstrations of the technological advancements achieved by Persian engineers and artisans. Their profound understanding of hydraulic and mechanical principles would influence both Eastern and Western technological developments.

## 22 *The Musician* 1772–1774

Film extract from the *Automates et merveilles* exhibition, 6:13 mins.
Musée d'art et d'histoire de Neuchâtel (Switzerland).
Direction: Philippe Calame.
©Musée d'art et d'histoire de Neuchâte/Rec Production, 2012.

### Henri-Louis Jaquet-Droz

was a Swiss watch-maker (1752–1791).

Designed by Henri-Louis Jaquet-Droz, *The Musician* is a remarkable example of human ingenuity. This automaton presses the keys of the keyboard with each of her fingers, playing on an organ whose bellows carry air to 48 pipes that are divided into two registers. *The Musician* breathes as she plays, ending each melody with an elegant seated bow. Jaquet-Droz was also a musician and it is likely he composed all five musical works played by the automaton. The 1.3 metre-tall *Musician* is made of an incredible amount of clockwork pieces made of brass, steel and lime wood. The automaton is mechanised by three motors. The first one controls the breathing, head and eye movements. The second, very powerful, gives the impulse to the arms to move along the keyboard and for the fingers to press on the keys. The last motor allows the *Musician* to finish each performance with a curtsey bow. In contrast to a music box, the *Musician* actually plays the piano with her ten mechanical fingers.

Henri-Louis's father, Pierre Jaquet-Droz, was a watchmaker and founder of the factory of the same name. Between 1768 and 1774, father and son, in partnership with Jean-Frédéric Leschot, built three very sophisticated humanoid automatas that were to make the company famous: *The Writer*, *The Draughtsman* and *The Musician*. Having travelled throughout Europe for over a century, the automatons were donated to the city of Neuchâtel in May 1909. They are now safely conserved at the Art and History Museum of Neuchâtel.

## 23 *Angel with Harp Automaton* c. 1890

Automaton with musical mechanism: 56 × 41.5 × 34 cm. Loan from the Museum of Music Automatons Seewen

This automaton is another example of an intricate mechanical device designed to play music, representing a unique intersection of art, engineering, and musical innovation deeply rooted in systematic thinking. Utilising principles of clockwork, musical automata could perform elaborate compositions through pre-programmed sequences of actions, essentially algorithms, bringing music to life without human intervention. In this instance, the angel turns its head, moves its wings. The two forearms make playing movements to the music of a cylinder musical mechanism. The whole mechanism is triggered by a small winding up mechanism a small clef on the side. Musical automata hold a significant place in the history of music, showcasing the ingenuity and creativity of their makers while providing insight into the cultural and technological context of their time.

## 24 *Portion of the Babbage Difference Engine No. 1* c. 1879

Scientific instrument: wood, brass, steel, paper, 33.6 × 31.8 × 38.5 cm.
Designer: Charles Babbage.
Manufacturer of parts: Joseph Clement.
Assembler: Henry Babbage
Wh.2339, Whipple Museum of the History of Science, University of Cambridge.

### Charles Babbage

was an English mathematician and polymath (1791–1871).

Between 1822 and 1834, Charles Babbage designed a Difference Engine, the ancestor of our modern computer. A difference engine is an automatic mechanical calculator designed to compute and tabulate polynomial functions. Such tables had important uses in the 18th and 19th centuries, in particular for navigation at sea. They were traditionally computed and typesetted by hand, a process that often introduced errors. In 1822, Babbage proposed that these human "computers" could be replaced by a machine, capable of performing calculations and printing the resultant tables, error free. The basic operation of the Difference Engine is to transform multiplication into addition by utilising the method of finite differences. This is achieved by 'programming' in a function and setting the machine going – though in this case it must be turned by hand.

The machine proved exceptionally complicated to build and Babbage was never able to successfully construct a working engine. After his death, his son Henry continued to work on the problem, having inherited original components made during his father's failed construction attempts. By recombining these components, Henry produced this partial fragment in 1879, as a means of demonstrating the feasibility of his father's design. Babbage's original design was to be a machine with seven axles, while this fragment has only two. So although it demonstrates the working of the Difference Engine, it can only perform very simple calculations. Indeed, it was used in the 1950s in Cambridge University's computer laboratories to demonstrate the automation of simple addition.

## 25 *Ada Lovelace's Notes* 1843

Book, 22.3 × 14.4 × 4.9 cm.
Published in Richard Taylor's *Scientific Memoirs* vol. III
By permission of the Master and Fellows of St John's College, Cambridge.

## Ada Lovelace

was an English mathematician and savant (1815–1852).

Ada Lovelace is known as the pioneer of computer programming. A mentee of Charles Babbage with whom she worked closely, she displayed remarkable foresight into the potential of computers to process symbols beyond just numbers. In her extensive notes translating an article on Babbage's Analytical Engine (a more accomplished and powerful machine design than the original Difference Engine, exhibit n°24), Lovelace speculated that the machine could manipulate symbols representing musical notes and compositions, anticipating modern digital music synthesis and composition.
As an accomplished musician herself, she realised the Analytical Engine's computing capabilities could extend to creating complex musical pieces by operating on the fundamental relations governing musical theory and notation.

Lovelace observed that by representing the fundamental relations of musical pitches and notation as symbols, the Analytical Engine could be adapted to compose complex musical pieces algorithmically. This profound leap showed her grasping the concept of symbolic processing and foreshadowed the modern use of computers for tasks like music synthesis and composition utilising algorithms and code. Lovelace's unique interdisciplinary perspective allowed her to glimpse the vast potential of general-purpose computers before they truly existed. Her vision paved the way for exploring computational creativity in the arts.

## 26 Arnold Schönberg

Music: A. Schönberg, *Suite, op. 29, II. Tanzschritte: Moderato*, 7:42 mins.

Arnold Schönberg (1874-1951) was an influential Austrian-American composer, teacher, music theorist, writer and visual artist, who pioneered twelve-tone music techniques. Born in Vienna and self-taught from a young age, Schönberg already composed piano pieces and string trios by age 10. His early works like the string sextet *Transfigured Night* (1899) were inspired by late Romantic composers. However, Schönberg soon broke from tradition, producing "atonal" pieces from 1908 onwards, intentionally departing from 19th century harmony. His most revolutionary innovation was the twelve-tone technique he developed in 1923, known as a dodecaphony. This involved arranging the 12 notes of the chromatic scale into unique rows or "series" with no tonal centre.

*Suite, op. 29*, also known as the *Suite for Seven Instruments*, is one of Schönberg's major twelve-tone works, composed in 1926. It was written for three clarinets (one doubling as bass clarinet), a violin, a viola, a cello, and a piano. This unique and unusual instrumentation contributes to the distinctive timbral palette of the piece, reminiscent of the reed section of a jazz swing band. The *Suite* consists of four movements. The second one, *II. Tanzschritte: Moderato* can be listened to in this installation. Schönberg fled Nazi Germany in 1933 and continued developing the twelve-tone system in the United States, teaching at universities. By the time of his death in 1951, Schönberg had cemented his legacy as one of the 20th century's most influential musical innovators.

## 26.1 *Suite op. 29, Score Movement 1 (Ouverture. Allegretto)* 1924–1926

Manuscript, Ink, pencil and coloured pencil on paper, 29 × 35 cm.
Arnold Schönberg Center, Vienna.

The cheerful, vibrant character of the *Suite, op. 29*, reflects Arnold Schönberg's mindset at the time. He was newly married and dedicated the work to his "dear wife" Gertrud, whose musical monogram "eS-G" (E flat-G) is interwoven into the musical events at the beginning and end of each movement. The four-part suite, in which elements of old tonality are incorporated into dodecaphony, combines three movements of the traditional baroque suite with a set of variations on a song. Dance-like rhythms dominate in a manner similar to several movements from his earlier piano compositions, whereby especially the first two movements use elements of the dance music of the 1920s.

## 26.2 *Suite op. 29, Twelve-tone row chart* 1924

Pencil and ink on paper, 36.8 × 36.5 cm.
Arnold Schönberg Center, Vienna.

A twelve-tone row (or series) is an abstract ordering of notes that serves as the foundation of a work created according to the "Method of composing with twelve tones which are related only with one another." Sometimes the complete row can be heard in the melody or accompanying voice. Schönberg usually worked with segments of the row or pitch combinations that derived from the original row and joined with each other in diverse ways. Melodies, harmonies, and polyphonic passages are created from individual collections of pitches, and the row usually remains in the background as a framework for musical ideas.

## 26.3 *Suite op. 29, Twelve-tone row chart* 1924

Ink on paper on cardboard,
21×34 cm.
Arnold Schönberg Center, Vienna.

In order to have a productive interplay between structural obligation and creative freedom, it is necessary to base compositional decisions on a deep understanding of the row, its derivations, and the possibilities that result therefrom. Schönberg expressed the pitch relations of a row, including its derivations, in different kinds of visual representations. With the first works that begin using his new kind of "composing with tones", he devised aids to facilitate compositional processes.

## 26.4 *Suite op. 29, Bidirectional twelve-tone row chart* 1924

Ink on paper on cardboard,
32.4×33.4 cm.
Arnold Schönberg Center, Vienna.

The lowermost red line contains the primary form of the row marked with the letter "T" – where the letter alludes to the tonic of conventional tonal harmony. After turning the page clockwise 90 degrees, Schönberg then used the pitches of the original row as starting pitches for twelve inverted forms of the row. Transpositions of the primary form then result from another clockwise turn of the box, and retrogrades can be read from right to left. Black and red slur lines subdivide the row into groups of three or four pitches. The corner pitches of the four-note groups are related to one another by the intervals of a fourth or fifth.

## 26.5 *Wind Quintet, op. 26, Twelve-tone row ruler* 1923

Typescript and ink on paper on cardboard, linen and split cord,
6.3×21.4 cm.
Arnold Schönberg Center, Vienna.

Arnold Schönberg used a custom-made slide ruler to aid in the composition of his *Wind Quintet Opus 26*. This slide ruler was specifically designed to help organise the twelve-tone rows in this serial composition. By using this tool, Schönberg could systematically (algorithmically) arrange and manipulate the twelve-tone sequences, ensuring the adherence to his compositional method.

# 27 CSIRAC

## 27.1 *CSIRAC computer* 1952

Image courtesy of CSIRO Archive
Music: Courtesy of Paul Doornbusch.

### Maston Beard, Trevor Pearcey & Geoff Hill

Maston Beard (1913–1998) was an Australian scientist and research engineer who was involved with radar research and he co-created CSIRAC.

Trevor Pearcey (1919–1998) was a British-born Australian scientist, who co-created CSIRAC, one of the world's first digital computers.

Geoff Hill, (1928–1982) was a mathematician and Australia's first computer programmer.

This large scale photograph shows CSIRAC (the Council for Scientific and Industrial Research Automatic Computer), the world's fourth computer and the first to play music. Developed in Australia, this massive machine weighed 2,500 kilograms and measured 2.5×3×7m, requiring industrial air conditioning. It operated with a clock speed of 0.001MHz, 2500 bytes of memory, and 2000 valves (vacuum tubes).

In 1951, CSIRAC achieved a significant milestone by playing music, demonstrating how early computers could engage with the arts. Mathematician Geoff Hill programmed the machine to play melodies. This event highlighted human creativity, programming ingenuity, and the computer's versatility rather than advancing musical technology. Although the original performance wasn't recorded, professor Paul Doornbusch led a project to accurately reconstruct CSIRAC's music. By analysing archival materials, technical schematics and personal recollections, and building hardware, his team simulated the historic sounds with extreme precision, preserving this unique moment in computing history.

CSIRAC's musical output reflects early curiosity about applying computing to the arts. CSIRAC did not directly influence future digital music developments. However, it marked a crucial moment when mathematical coding and musical expression first converged in the digital realm, exemplifying the human desire to explore new machines' artistic potential.

## 27.2 *CSIRAC Computer Programme Tape* c. 1951–1952

Punched paper program tape,
6 cm×7 m. Music tapes storage box, 6×6×20 cm.
On loan from Paul Doornbusch.

### Geoff Hill

was a mathematician and Australia's first computer programmer (1928–1982).

This punched paper tape is the original music programme tape used to programme CSIRAC to play music. Geoff Hill worked with CSIRAC from the beginning. He used the programming of CSIRAC to play music as an extreme programming challenge. By encoding notes as numbers on a punched paper tape, the engineers were able to get CSIRAC to generate audio and play a very basic tune through the attached speaker. While primitive by today's standards, this pioneering experiment demonstrated the potential of using computers to generate and play back musical compositions directly from programmed instructions.

# 28 Iannis Xenakis

Iannis Xenakis (1922–2001) was a pioneering Greek-French composer, architect, and mathematician who is renowned for his ground-breaking work in algorithmic and computer-assisted composition. Born in Romania, he fought in the Greek resistance during World War II, losing an eye in the process. After being exiled from Greece due to his political activities, he moved to Paris, where he worked as an architect with Le Corbusier and designed the iconic Philips Pavilion for the 1958 Brussels International Exhibition.

Xenakis' musical journey took a significant turn when he began studying with Olivier Messiaen, who encouraged him to embrace his mathematical background and Greek heritage in his compositions. This led to Xenakis development of stochastic music, a revolutionary approach that utilised computer programmes, mathematical structures and probability systems to generate musical pieces. Works like *Metastasis* (1954) and *Achorripsis* (1958) were pioneering examples of this technique, which he later refined using IBM computers to control various musical parameters.

Xenakis' contributions extended beyond algorithmic composition, as he also created groundbreaking electroacoustic works and developed the UPIC system, which could translate graphical images into musical results. His compositions pushed the boundaries of traditional music, exploring the intersection of art, science, and nature. Despite the mathematical underpinnings of his approach, Xenakis' music is renowned for its raw power and emotional impact.

## 28.1 *Xenakis Archives* 1954–1994

Interactive installation.
Linear Navigator, 55 inch LCD screen on a 12 m long rail.
Manufacturer: Nelissen Decorbouw.
Archive contents courtesy of Famille Iannis Xenakis.
Production: EPFL Laboratory for Experimental Museology (eM+).
Software Application: Nikolaus Völzow. UIX design: Patrick Donaldson.

Thanks to the Linear Navigator, the public can browse some 2,000 images from the Xenakis archives. This unique collection offers an unparalleled glimpse into the composer's mind and the fusion of mathematics with music. Each image serves as a visual testament to his unique approach, capturing the intricate graphical working and scores, mathematical models, and algorithmic notations that underpinned his innovative work.

From the geometric patterns of *Metastasis* to the stochastic processes of *Pithoprakta*, these images reveal how Xenakis translated complex mathematical concepts into evocative sonic experiences. His use of graphs, curves, and architectural drawings illustrates a visionary method where visual art and scientific rigour coalesce to create revolutionary music.

With the Linear Navigator a visitor can explore the interplay between structure and creativity in Xenakis' compositions. This archival collection is indispensable for understanding the depth of Xenakis' contributions to music and his enduring influence on contemporary composition.

## 28.2 *Philips Pavilion, Expo 58* c. 1957–1958

Model: metal, wood and polyester, circa 110×175×85 cm.
Rijksmuseum, on loan from Philips International BV.

# Iannis Xenakis & Le Corbusier

At the invitation of Philips, the Dutch electronics firm, the architects Le Corbusier and Xenakis designed a pavilion for Expo 1958, the world's fair held in Brussels. The concrete building was coated with aluminium paint. Inside there was a multimedia show with film, coloured light and electronic music. Planes of colour in the entrance set the tone for the 'electronic performance' inside, which attracted one and a half million visitors. The building is based on the mathematical construction of "hyperbolic paraboloids", which Xenakis was also working with in his music, and shows how he used a single concept and expressed it through both architecture and music.

## 28.3 *UPIC* 1985

Digital Computer System for music creation, 200×200×100 cm.
On loan from KSYME/CMRC Archives, Athens Conservatoire.

The UPIC (Unité Polyagogique Informatique du CEMAMu) system is a digital computer system invented by Iannis Xenakis. The computer converts the graphic representation drawn by the user on the interface board into sound. The Greek UPIC (*Polyagogia*) was inaugurated in 1986 by the Contemporary Music Research Centre (KSYME, founded in Athens in 1979 by Xenakis and 24 other members) with the aim of promoting research in computer music. It allowed users to draw musical scores directly onto a graphics tablet, translating visual designs into intricate sonic landscapes. Xenakis sought to democratise the composition process and make it accessible to those without formal musical training, and his vision materialised in the UPIC system. Xenakis was inspired by the idea that music could be composed through visual means, reflecting his background in architecture and mathematics. The UPIC system encapsulated this interdisciplinary approach, offering a new medium for artistic expression. This innovation bridged the gap between visual art and music, offering unprecedented creative possibilities.

# Player Piano Room

This section explores the evolution of automated music through the player piano, or pianola. Rooted in 18th century musical automata, the player piano developed from barrel organs and orchestrions. Edwin Scott Votey patented the first true “Pianola” in the 1890s, leading to widespread popularity by the early 20th century.

Traditional player pianos use foot-pumped pneumatics to read perforated paper rolls, activating piano keys to play the piece. This technology democratised access to complex compositions and preserved notable performances, becoming the first musical recording and playback medium.

After peaking in the 1920s, the player piano’s popularity waned with the advent of radio and phonographs. Nevertheless, it remains a cherished symbol of early 20th century ingenuity in automated music.

The exhibited Yamaha Disklavier exemplifies the player piano’s digital evolution, combining historical innovations with modern computer technology. It allows for precise reproduction and creation of complex musical works. The latter demonstrate how contemporary composers continue to explore automated musical performance, pushing beyond human physical limitations.

With the generous support of Yamaha Europe GmbH, (Swiss branch).

# 29 Player Piano Music

## 29.1 *Study 41B* 1969–1977

Music: Courtesy of Sam Sansom.
Visualisation video: 6:36 mins, ©Stephen Malinowski, musanim.
Digital reproduction of the original score with pencil entries. Conlon Nancarrow Collection, Paul Sacher Foundation, Basel.

### Conlon Nancarrow

was an American-born composer and pioneer in algorithmic music (1912–1997).

The digital reproduction of Nancarrow’s *Study 41B* score demonstrates the composer’s interest in complex rhythmic structures. This led him to the player piano, an instrument that could execute his compositions with a precision impossible for human performers. Nancarrow used the technique of hand-punching holes into piano rolls, which enabled him to control many aspects of the performance, including tempo, dynamics, and intricate rhythmic patterns. This allowed him to explore temporal and metric complexities, layering rhythms at different speeds and creating polymetric textures that were unprecedented. For a time forgotten and unknown, Nancarrow’s *Studies for Player Piano* are particularly renowned, consisting of more than fifty pieces that push the boundaries of musical time and rhythm. These works often employ algorithmic techniques, using mathematical and mechanical processes to generate complex timing and musical structures. Nancarrow’s compositions are often characterised by their use of temporal canons, where melodies are played at different speeds simultaneously, creating intricate and often dizzying effects.

## 29.2 *Étude 14A* 1985

Music: Courtesy of the Jörgen Hocker Archives.
Visualisation video: 1:52 mins, ©Stephen Malinowski, musanim.
Digital reproduction of the original annotated score. György Ligeti Collection, Paul Sacher Foundation, Basel.

### György Ligeti

was a Hungarian-Austrian composer of innovative and algorithmic music (1923–2006).

This colourful sketch of *Étude 14A* is scribbled with Ligeti’s annotations and shows the great intricacy of his music. His work in the 1960s and beyond is characterised by its use of complex textures and structures that often resemble algorithmic processes. His interest in mathematical processes and algorithmic composition is perhaps most evident in his later works. In the 1980s and 1990s, Ligeti explored the use of fractals and chaos theory in music, particularly in his *Études for Piano*. Many of the études employ intricate, algorithmic rhythmic patterns and structures that challenge both the performer and the listener. *Étude 14A*, originally named *Coloana fără sfârşit* (Column without end), is a piece written specifically for the player piano. It explores interwoven rising patterns of thick chords and alludes to aural illusions such as the infinite Shepard tones scale, which seems to rise without end. In its setup, the composition lies at the very border of the humanly possible – even though several pianists have now worked with this composition.

## 29.3 *Voyager* Since 1986

Music: by George Lewis, with kind permission.
Video of computer program performance, edited from the original: 21:27 mins. Laboratory for Experimental Museology (eM+), EPFL.

### George Lewis

is an American composer, musicologist, and trombonist.

*Voyager* is a pioneering software system created by George Lewis, allowing human improvisers to engage in real-time dialogue with an interactive "virtual improviser" programme. The software analyses the performers' music live and generates complex responses, capable of producing independent musical behaviour without real-time input. Initially, *Voyager* featured a concerto setting where human players interacted with a 64-voice multitimbral and microtonal electronic orchestra of synthesised voices. Post-2004, it evolved into an interactive improvising pianist, performing with soloists, chamber ensembles, and symphonic orchestras.

*Voyager* is deeply influenced by Lewis' extensive experience as an experimental improviser. Its sonic and listening behaviours result from negotiations between the improvising performers and interactions among numerous differentially timed music generation algorithms. These algorithms track parameters such as pitch, volume, duration, accent, silence, and interval width. This enables them to assess more important factors over time, such as the degree of stability. Post-2022 versions incorporate machine learning algorithms to recognise musical gestures, creating a metastable and quasi-predictable system with short-run variability, defining *Voyager's* unique "personality" or "identity."

Lewis, a member since 1971 of the influential African American experimental music collective AACM (Association for the Advancement of Creative Musicians), is widely regarded as a pioneer in computer music systems that improvise alongside human musicians. His work has been at the forefront of avant-garde and experimental music for over five decades, demonstrating the innovative potential of interactive computer music systems in live performance.

## 29.4 *OTOdeBLU* 1990

Music: Courtesy of Birgit Faustmann.

### Clarence Barlow

was a pioneering composer known for his work in electronic and computer music (1945–2023).

*OTOdeBLU* for player-piano is an innovative piece that showcases Barlow's distinctive approach to algorithmic composition, where mathematical processes are used to generate musical structures.

## 29.5 *Continuity 4* 2015

Music: courtesy of Paul Doorbusch.

### Paul Doornbusch

is a composer, musician, and academic known for his contributions to computer music, algorithmic composition, and digital cultural heritage.

*Continuity 4* for player-piano is based on fractal noise, it explores the dynamic interplay between continuity and fragmentation in pitch, timbre, and time, creating a complex and evolving auditory experience.

## 29.6 *Arabesque* 2018

Music: Courtesy of Nicolas Namoradze.
Composition for solo piano, 6 mins. Published by Muse Press.

### Nicolas Namoradze

is a pianist and composer, working in New York.

Nicolas Namoradze's *Arabesque* is based on principles that define arabesques in visual art: those of ornate, spiralling and interlacing patterns. The pianist's hands are superimposed throughout the work, playing intertwined figurations where the individual strands can only be distinguished by dynamic shifts between the hands. Two types of sections alternate with each other – one ascending, the other descending – creating a slow oscillation in the upper half of the keyboard. A study in gentle changes of colour and sonority, the shifts between various textures occur extremely gradually throughout the work, in a manner reminiscent of German graphic artist M.C. Escher's *Metamorphosis* prints.

The timing and rate of these shifts is controlled by a number of algorithms. The first of these is the simplest, transforming the texture from a two-part counterpoint – where the right hand has short ascending figurations, the left hand descending – to a one-part hocket between the hands, effected via an increasingly frequent omission of notes. Following this, a gradual introduction of triadic chords as well as accented triadic motifs thickens the texture, reaching a dynamic and register climax before another steady dissolution. The final set of transformations are not only textural but also temporal: short bursts of accelerated figurations appear frequently enough over time to cause a global change in speed, eventually sending the passagework (section of a musical composition consisting especially of ornamental figures) spinning off forever.

## 30 *The Concert Room*

The Concert Room is a space designed for an immersive experience. It showcases two algorithmic musical pieces: Luigi Nono's *Prometeo. Tragedia dell' ascolto* and Iannis Xenakis' *La Légende d'Eer*. This Room offers an audio environment to experience these works as they were intended, with immersive spatialisation and acoustic detail. The arrangement of speakers and acoustics replicates as closely as possible the original performance settings, allowing the listener to fully appreciate the intricate spatial and algorithmic elements of these visionary compositions.

## 30.1 *Prometeo. Tragedia dell'ascolto*

## 1984–1985

Three excerpts from the full recording, approx. 2 hours.

## Luigi Nono

was an Italian composer (1924–1990).

*Prometeo. Tragedia dell'ascolto* (Prometheus. Tragedy of Listening) is one of Luigi Nono's most ambitious works. This monumental piece is a unique fusion of music, theatre, and spatial acoustics, designed to immerse the audience in a deeply reflective listening experience.

Known for his avant-garde and politically charged works and a member of the Darmstadt School, Nono was deeply involved in the post-World War II development of serialism and electronic music. His compositions often reflect his commitment to social and political issues, integrating innovative techniques and technologies to challenge and expand the boundaries of musical expression. The work is structured as a series of musical and textual fragments, drawing from various sources including Aeschylus, Goethe, and Hölderlin. It does not follow a conventional narrative but rather creates a meditative and contemplative soundscape. Nono's innovative use of live electronics, spatialisation, and unconventional orchestration envelops the listeners, making them an integral part of the auditory experience.

*Prometeo* was conceived in collaboration with philosopher Massimo Cacciari and architect Renzo Piano, who designed the mobile structure in which the piece was originally performed. This setup allowed for dynamic manipulation of sound within the performance space, emphasising Nono's exploration of the relationship between sound, space, and listener.

*Prometeo. Tragedia dell'ascolto* is a testament to Nono's revolutionary vision, challenging traditional forms and inviting audiences to engage in a profound act of listening. It remains a significant work in the canon of contemporary music, exemplifying Nono's relentless pursuit of new musical and expressive possibilities.

## 30.2 *La Légende d'Eer*

## 1977–1978

Two excerpts of 6–7 mins each & full recording of approx. 45 minutes.

## Iannis Xenakis

was a Greek-French composer, architect, and engineer (1922–2001).

*La Légende d'Eer* is one of Iannis Xenakis' seminal works in electronic music and spatial performance. Commissioned for the opening of the Centre Georges Pompidou in Paris, it was performed in the Diatope, a specially designed architectural and acoustic space designed by Xenakis himself.

The piece draws inspiration from the myth of Er in Plato's *Republic*, which describes a soldier's journey through the afterlife. Xenakis translates this narrative into a sonic experience, using electronic sounds to evoke otherworldly and transformative aspects.

Notable for its immersive environment, *La Légende d'Eer* utilises a complex array of loudspeakers to project sounds throughout the Diatope. A light show featuring hundreds of flashbulbs, lasers, and computer-controlled mirrors enhances the sensory experience. The composition employs a rich palette of electronic sounds, including granular synthesis and complex noise textures, reflecting Xenakis' mastery of stochastic processes and mathematical models.

Structured as a continuous flow of sound without clear divisions, the piece invites listeners to engage deeply with the evolving soundscape. It exemplifies Xenakis' revolutionary approach to music, combining his architectural vision with innovative use of technology and sound.

*La Légende d'Eer* stands as a landmark in electronic music history, showcasing Xenakis' unique ability to blend intellectual rigour with profound artistic expression.

# Electronic Music

This section explores the innovative realm of electronic music, showcasing works like Karlheinz Stockhausen's *Studie II* and John Cage's *Fontana Mix*. These pieces exemplify technology's transformative impact on music creation, highlighting synthetic sound generation and tape manipulation techniques.

Open-reel tape recorders, introduced in the 1930s and 1940s, revolutionised music composition and editing. Pierre Schaeffer pioneered *Musique Concrète*, manipulating recorded natural sounds to create new sonic textures. The WDR studio in Cologne became a hub for electronic music experimentation, with Stockhausen producing seminal works combining human voice recordings with electronically generated sounds.

Early electronic music utilised basic engineering tools like oscillators and filters to create and shape sound waves. Stockhausen's *Studie II* employed these techniques, using tape recording for overdubbing. The invention of voltage-controlled synthesisers in the 1960s by Robert Moog and Don Buchla allowed for more complex sound modulation. Many composers employed tape manipulation in their works, such as John Cage, Vladimir Ussachevsky, Milton Babbitt, and Steve Reich, Pierre Schaeffer and Pierre Henry, Hugh Le Caine, Daphne Oram, Edgard Varèse, Luciano Berio, Luigi Nono.

Copying between tape machines, tape manipulation and multiple tracks became fundamental to popular music in albums such as The Beach Boys *Pet Sounds* and The Beatles *Sergeant Pepper.*

## 31 *Studie II* 1954

Video by Georg Hadju, 3:25 mins, looped.
Sound recording & printed music score: Karlheinz Stockhausen, STUDIE II/STUDY II Electronic Music (1954).
Photographs: Courtesy of WDR Archives.

## Karlheinz Stockhausen

was a German composer and electronic music pioneer (1928–2007).

*Studie II* by Karlheinz Stockhausen is a seminal work of his career and in the history of electronic music. He composed his work in 1954 at the Westdeutscher Rundfunk (WDR) in Cologne, using tape splicing and overdubbing techniques that enabled additive synthesis to be applied. The enlarged black and white photograph presents the said WDR studio. *Studie II*, along with its predecessor *Studie I*, represents some of the earliest explorations into purely electronic sound composition. Unlike traditional compositions, *Studie II* employs synthetic sounds generated and manipulated through electronic means, including sine waves, filtering, and amplitude modulation.

The composition of *Studie II* involves meticulous planning and mathematical precision. Stockhausen used serial techniques to control various parameters of the sound, such as pitch, duration, dynamics, and timbre. The result is a complex and abstract soundscape that challenges conventional notions of melody and harmony. The projected video together with the printed score, allow visitors to read and understand the complexity of Stockhausen's work.

Indeed, the composition is structured into 81 sections, each carefully crafted to produce a distinct sonic experience. Stockhausen precisely calculated these frequencies to establish an exact serial framework, highlighting mathematical correlations between pitches. Furthermore, he employed subtractive synthesis techniques, utilising filters to shape white noise, which added to the piece's timbral intricacy.

This piece reflects Stockhausen's belief in the transformative power of electronic music and his commitment to expanding the boundaries of musical expression. The work's influence extends beyond the realm of electronic music, impacting avant-garde composition and sound art.

*Studie II* remains a landmark in the history of music, demonstrating the potential of electronic media in creating new sonic experiences.

## 32 *Fontana Mix* 1958

Original recording, approx. 15:44 mins.
Printed score: Fontana Mix by John Cage © 1960 Henmar Press Inc., New York. Used by permission of Faber Music Ltd. All Rights Reserved.
Photograph: image courtesy of the John Cage Trust.

## John Cage

was an American composer, music theorist, writer, and artist (1912–92).

*Fontana Mix* was composed by using a complex, chance-derived pattern for splicing together fragments of magnetic tape, chosen from six categories of sound: city, country, electronic, manually-produced (including music), wind-produced, and small sounds requiring amplification. Cage made use of a new graphical system for determining the choice and editing fragments. He also made use of a set of graphical diagrams on clear plastic as a tool to make versions of the piece. Points are selected on curved lines to represent the type of sound, means of modifying amplitude, frequency and timbre, and duration. Transparencies are overlaid in various combinations above the straight lines, which provide reference for measurements. Here, the algorithm is present in the tape editing process led by the musician, rather than in symbolic manipulation of sounds.

Cage's original version was made at the Studio di Fonologia in Milan in 1958, assisted in the laborious tape slicing and copying process by Marino Zuccheri. Made in the era before multi-track recording, it is made for four single-track or two stereo tapes. The original piece may be played in combination with a live musician performing certain other works by Cage. Work, materials, composer, performer and environment come into new and dynamic relationships.

## 33 *Revox G36* 1966

Tape recorder made of plastic, electronics, tapes, metal, 29.5×47.7×34.1 cm. Reels: 26.5 cm ø. Manufactured by Revox.
On loan from the SMEM, Swiss Museum and Center for Electronic Music Instruments.

The Swiss Revox company, founded in 1951 by Willi Studer, is well-known for its high quality audio equipment. Among their most iconic products is the Revox 36G tape recorder. This device was innovating as it was the first tape recorder to incorporate a synchronous motor as the capstan (tape drive) motor, which significantly enhanced its audio precision and stability. The G36 offered two tape speeds (3.75ips and 7.5ips) and dual-track capability, making it versatile for various recording needs. Also renowned for its robustness and reliability, it soon became a staple for both professional studios and high-fidelity home studio systems.

This type of reel-to-reel tape recorder was typical of those used in electronic music studios and for pieces involving tape editing techniques. The composer placed the tape in a groove on the editing block and marked edit points with a grease pencil before cutting the tape using a razor blade. To join two pieces of tape, the ends were aligned in the editing block and a small piece of adhesive splicing tape was applied to the back. Composers could create effects by reversing tape segments, forming loops, or altering playback speed. This meticulous process allowed for the creation of innovative compositions involving many hundreds of edits that were impossible to achieve through traditional musical notation or performance.

## 34 *Buchla 200e Skylab* 2012

Analogue synthesiser: wood, electronics, plastic, cables, 18×58×38 cm.
Manufactured by Buchla. Private collection.

The Buchla 200e Skylab, introduced in 2012, is a compact yet powerful modular synthesiser that encapsulates the essence of Buchla's innovative approach to electronic music. Since the early sixties, Buchla has been known for its unique and experimental designs. Its founder, Don Buchla (1937–2016) was a pioneering American inventor and composer renowned for his significant contributions to the field of electronic music. Buchla's most notable invention is the Buchla Series 100, one of the first modular synthesisers, created in 1963. The 200e Skylab continues this legacy by transposing the renowned Buchla DNA to a portable and flexible system. This synthesiser combines digital and analog technologies, providing a vast array of sonic possibilities for live performance and complex sound design. Its modular nature allows users to customise and expand their setup, fostering creativity and exploration. The Skylab's distinctive interface, with its touch-sensitive controls and visual feedback, facilitates intuitive and expressive music-making. It is particularly favoured by musicians seeking to push the boundaries of sound and explore new auditory landscapes. Early analog electronic synthesisers have been instrumental in shaping the history of electronic and algorithmic music, offering composers and musicians new tools for sound creation and manipulation.

## 35 *Expert Senior Gramophone* 1930

Gramophone: wood, papier-mâché, metal, 178×74×122 cm. Manufactured by E.M.G Handmade Gramophones. Private collection.

The gramophone on display is the first to have possessed an essential quality: the shape of the horn which follows a mathematically calculated acceleration in its diameter. The acceleration starts right behind the soundbox, goes through the tonearm and the inner tubes up to the mouth of the horn. The latter is made of papier-mâché around a thin supportive structure to minimise resonance and reflections. The soundbox is constructed to allow tuning, minimising the loss of information from the record groove and providing optimal sound quality. These gramophones are reputed to be the best ever produced.

Early gramophones, phonographs, and record players have profoundly impacted music development, including electronic and algorithmic genres. Invented by Thomas Edison in 1877, the phonograph was the first device capable of recording and reproducing sound. This technology revolutionised music experience and production. The impact of this technology is still very much present; if today's pop songs are about three minutes long, it's because Edison's cylinder disc could only store three minutes' worth of music.

The influence of these early devices extends to contemporary music, enabling sound to be treated as data. Digital samplers and software now emulate techniques developed by early electronic and algorithmic musicians. These innovative technologies laid the groundwork for sound manipulation and algorithmic processes, continuing to shape contemporary music.

## 36 *The Hands* 2000

Electronic instrument: 40×30×30 cm.
Technician: Jorgen Brinkman, STEIM.
Video, 3:29 mins, looped.
Courtesy of the Michel Waisvisz Archives.

## Michel Waisvisz

was a pioneering Dutch composer, performance artist, musician, and inventor (1949–2008).

*The Hands* revolutionised live electronic music performance. First developed in 1984, they consisted of two controllers, worn on the performer's hands, equipped with sensors that could detect various hand movements and gestures. These movements were then translated into control signals, allowing the performer to manipulate sound parameters such as pitch, volume, and timbre in a dynamic and nuanced manner. The device utilised technologies like infrared and ultrasound sensors, and accelerometers to capture the performer's gestures, making it one of the first wearable controllers in electronic music.

Waisvisz's invention allowed for an unprecedented level of expressiveness. Unlike traditional keyboard-based synthesisers, *The Hands* provided a direct and physical way to interact with electronic sounds, making the performance more engaging and visually compelling.

The impact of *The Hands* on electronic music opened up new avenues for live performance and improvisation, influencing a generation of electronic musicians and composers. Waisvisz himself used *The Hands* extensively in his performances, demonstrating their potential in various musical contexts.

The legacy of Michel Waisvisz and *The Hands* continues to inspire contemporary developments in musical interface design. His work encouraged the exploration of new forms of human-computer interaction in music, emphasising the importance of physicality and gesture in the creation and performance of electronic music.

## 37 *Lady's Glove v.4* 1994

Electronic Wearable glove: lycra, 19 electronic sensors, 66×14×5cm.
Inventor: Laetitia Sonami.
Engineer: Bert Bongers.
Video: *Sonami in Guagshou — 2012*, produced by Brian Laczko. 01:21 mins, looped.

## Laetitia Sonami

is a French-born musician working in Oakland, California.

Laetitia Sonami's groundbreaking works explore themes of presence, participation, and the immediacy of sound, place, and objects. She is best known for her iconic *Lady's Glove*, of which the currently exhibited item is the fourth version. The elbow-length glove is fitted with numerous sensors that could translate her hand and body movements into sound, presaging today's wearable technology.

Sonami is a pioneering sound artist, performer, and researcher who has pushed the boundaries of electronic music and gestural performance. Born in France, she relocated to the United States in 1975 to immerse herself in the emerging field of electronic music, studying under pioneering figures like Eliane Radigue, Joel Chadabe, Robert Ashley, and David Behrman. After retiring the glove in 2015, she created the *Spring Spyre*, a new instrument that applies neural networks to real-time audio synthesis.

# AI & Music

There There is a long history of rule-based approaches to music in its imagination, creation, education, or automatisation. The information age brought this into a fertile phase, from Hiller and Isaacson's 1957 *Illiac Suite* on a room-sized computer to recent publicly-accessible machine learning technologies generating soundtracks or pop songs from simple prompts.

Recent AI developments transform music's creation, reception, and understanding, dealing with vast data and engaging our information-saturated world. Much effort has been invested in generating known styles of music, its imitation, and recommendation.

This exhibition proposes new approaches, addressing performance, listening, human creativity, authorship, post-human ethics, and global culture. *Polyp* by Poliks and Trillo reminds us of constant surveillance and evolving sound-based life. Lewis' *Voyager* embodies deep creativity and musicianship. *On the Nature of L.A.R.S.*, Wollny and Rohrmeier explore a human-machine live interaction on the piano. Cardenas' *Life Codes* brings us into direct contact with the computer. *Apollo e Marsia*, by Impett, explores time and human memory. Walshe critically examines *13 Ways of Looking at AI, Art & Music*.

## 38 *On the Nature of L.A.R.S.* 2024

Development: Joris Monnet, Martin Rohrmeier, Ioannis Rammos. Video: Matthias Grunder. Management: ACT Music.

# Michael Wollny and Martin Rohrmeier

Michael Wollny is a German jazz pianist & professor of Jazz piano at the Hochschule für Musik und Theater Leipzig.

Martin Rohrmeier is professor of Digital Musicology at the EPFL.

*On the nature of L.A.R.S.* documents jazz pianist Michael Wollny duetting with a musical machine on the Disklavier. Co-developed by Michael Wollny and Martin Rohrmeier, *L.A.R.S.* is a system with the overlapping capacities to *Listen*, *Act*, *React*, and *Silence*, embodying a reflection on the core of the creative process and a self-standing aesthetic, acting as an extension of the authors' musical minds. *L.A.R.S.* remembers, mirrors and transforms the music it receives and creates original incentives in the improvisational flow. More than a script, it expresses itself in countless interactive performances. A suite of short encounters explores this space of human-machine interaction and invokes spontaneous forms of musical exchange. In a musical rendezvous, *L.A.R.S.* and its human partner get to know each other and jointly explore the relationship between creativity, rules, freedom, and spontaneity. The work is also a personal engagement of its creators with the history of rule-driven and algorithmic composition, including figures like Machaut, Frescobaldi, Nancarrow, Ligeti, Stockhausen, and Lewis. It connects the history of player pianos and computational musical agents to the developments of machine interaction from ELIZA to modern AI.

## 39 *Life Codes* 2024

Interactive immersive display, 60 mins, looped. Composer, lead artist: Alexandra Cárdenas. Visual artist: Roger Pibernat. Programmer, interaction designer: Patrick Borgeat. Production assistant: Nikita Freeboid Khudiakov.

# Alexandra Cárdenas

is a composer and live coder, working in Berlin, originally from Colombia.

*Life Codes* introduces audiences to live coding performance practice and to the art of programming algorithmic music. By demystifying the inner workings of algorithmic musical thought, the artist sheds light on how computers expand the horizons of real-time music creation. *Life Codes* aims to broaden the accessibility of live coding beyond specialised groups, believing that artistic expression and technological education should be inclusive and participatory. The installation transforms code manipulation into an engaging and immersive experience. Visitors encounter drifting fragments of computer code, accompanied by visual imagery and sounds. By scanning the QR code with their phone or tablet, users are assigned a cursor that appears on the walls. Participants can then manipulate the code fragments with intuitive gestures, seamlessly linking different pieces and influencing sound and image in real time, to create new compositions and visualisations. Through tangible and intuitive interaction with the code, participants become active creators and develop a deeper connection with the creative process. Ultimately, *Life Codes* seeks to trigger curiosity, creativity, and a renewed appreciation for the connections between music, machines, algorithms, digital technologies, and human expression.

## 40 *Apollo e Marsia* 2024

Video, resonators and AI. Alto flute: Richard Craig. Viola d'amore: Marco Fusi. Videographer: Shivadas De Schrijver. Sound engineer: Juan Parra Cancino. Instrument builders: Magno Caliman, Elisabeth Salverda. Programmer: Leonardo Impett

# Jonathan Impett

is a composer, trumpet-player and researcher, currently Director of Research at the Orpheus Instituut, Ghent.

This work expands the moment in time represented in Tintoretto's painting *La gara tra Apollo e Marsia* (c. 1545). Apollo, playing a viola da braccio with sympathetic strings, has been challenged by the satyr Marsia, playing a long wind instrument, to see who is the greater musician. Based on Ovid's *Metamorphoses* Apollo will win, but in the moment depicted the two protagonists are waiting for the judgement of King Midas.

*Apollo e Marsia* is an installation consisting of two large screens displaying performances of compositions for viola d'amore and alto flute in changing patterns of fragments. The viola sound is processed through two long tubes, the flute through two long strings as their performances modulate each other. In addition, both are constantly listening to each other and to changing sounds in the room through machine learning networks, generating new memories that may predict, remind or surprise.

The piece is therefore a play on the nonlinearity of memory under stress; moments are recalled, replayed or intrude, but are always changing in their reconstruction. Apollo and Marsia listen to each other, trying to second-guess the other's memory. At their root, these sonic memories all derive from two hymns to Apollo inscribed in stone at the temple dedicated to him in Delphi. Arguably the earliest remaining instances of music notation, and likewise fragmented by erasures, these hymns embody partially-lost memory that we attempt to reconstruct.

## 41 *13 Ways of Looking at AI, Art & Music* 2021–2024

# Jennifer Walshe

is an Irish composer and performer, working in London and Roscommon.

In 2023, Jennifer Walshe wrote a highly-influential essay titled *13 Ways of Looking at AI, Art & Music*, offering radical new ways of thinking about what AI is and does. This room features five works by Walshe: AI as Fan Fiction, as Energy Drink, as Conceptual Art, as Companion Species, as Nature, the Ineffable. Each encapsulates the 13 ways of looking at AI.

Walshe notes that: "Ai is not a singular phenomenon […] but it is many, many different things – the fantasy partner chatbot whispering sweet virtual nothings in our ears, the algorithm scanning our faces at passport control, the playlists we're served when we can't be bothered to pick an album. The technology is similar in each case, but the networks, the datasets and the outcomes are all different.

The same goes for art and music made using AI. We can listen to Frank Sinatra singing a cover of a rap song from beyond the grave, we can look at paintings made by robots, we can hang out in the comments section of a machine learning-generated death metal livestream. But the fact that artworks like these are made using AI doesn't mean that they are all asking the same questions or have the same goals. We experience these works — and the way AI is used in them — in a multitude of ways. So, instead of looking for a definitive approach [...], perhaps we should try and think like the networks do – in higher dimensions. From multiple positions, simultaneously. Not one way of looking at AI, but many."

The full text can be accessed using the QR link below.

## 41.1.A *The Text Score Dataset 1.0* 2021

Panels, score on t-shirt, dataset in 12 volumes.

## Jennifer Walshe

The text score – written instructions involving no standard musical notation – is one of the most democratic and powerful forms of notation. Initiated as a form by Marcel Duchamp (1887–1968) and subsequently pioneered by John Cage in the late 1950s, the text score was quickly taken up by artists, writers, musicians and film-makers. In 2017, Jennifer Walshe began gathering text scores, to form a dataset which could be used to train a machine learning system to create new scores. Each text score was transcribed and then generated into metadata. The result was a dataset of over 3,000 text scores – a corpus of approximately half a million words.

In 2021, the PRiSM Centre at the Royal Northern College Music commissioned the completion of the first stage of the project. In collaboration with PRiSM co-founder David DeRoure, professor at the University of Oxford's Department of Engineering Science, Walshe and her assistant Ragnar Ámi Ólafsson, produced the outputs seen in the exhibition and in the booklet from the project.

"**#2**: Energy Drink. AI is an energy drink. It enables you to do more, for less. Why make one score when you can make hundreds?"

The *Text Score Dataset 1.0* booklet is available online for download at no cost (see QR code below). The scores exist to be played freely, by anyone.

## 41.1.B *The Text Score Dataset 1.0* 2021

Jigsaw puzzle, inflatable saxophone, rulers, crystal trees, plastic soldiers & animals, bubble wrap, radio, emergency blanket, recorder, tape.

Discarded props and traces of performances of the AI-generated scores from *The Text Score Dataset 1.0* can be found in the space; scrapes of evidence of the human activation of computer-generated art.

## 41.2 QUANTA 2018

Video, 42:41 mins, taken from a 60 min-long film.

## Tomomi Adachi & Jennifer Walshe

Jennifer Walshe and Japanese composer and performer, Tomomi Adachi, are long-standing collaborators who both share an interest in AI. Adachi's award-winning *Tomomibot* is an AI sys-tem based on his voice. In 2018 Adachi and Walshe conducted a highly conceptual performance in a hotel room in Luxembourg. They used a Ouija board to hold a séance, in order to con-tact an "AI from the future." They luckly made contact with a being which identified itself as "Quanta," who answered their queries about how AI would develop. The performance poses questions about what humans' hopes for AI are, as well as our feelings of agency in relation to it.

"**#6**: The Ineffable. AI is the Ineffable. It is a way to use language to access something beyond language, a route into particular ideas about timeless musical genius."

## 41.3 OSCAILT 2023

Video, 7:16 mins. Commissioned by Music Network Ireland. Performed by Panos Ghikas, Elizabeth Hilliard, Nick Roth & Jennifer Walshe.

## Jennifer Walshe

Ireland has become the land of data centres, tech corporations and fibre optic cables moving information at vast speed from the Atlantic through to Europe and beyond. OSCAILT, an hour-long music theatre piece, seeks to interrogate what this means for Ireland's youngest generation, the so-called digital natives. Do Irish androids dream of electric sheep? Neon Aran jumpers? Psychedelic mediaeval illuminations? The video shown here, taken from the final section of the piece, begins with a simple image – Irish teenagers and their smartphones – and uses AI to drift through the network's understanding of the Emerald Isle, gradually pulling back to reveal a cosmic landscape.

"**#10**: Nature. AI is nature. Generative AI functions because it is built on top of huge datasets comprised of scrapes of the internet. We live in and contribute to these datasets on a daily basis, whether or not we ever use generative AI. Data is the true landscape now."

## 41.4 ULTRACHUNK 2018

AI system for live performance.
Video, 23:12 mins.
ULTRACHUNK was commissioned by Somerset House Studios with the generous support of the Case Foundation.

# Memo Akten & Jennifer Walshe

ULTRACHUNK is a collaboration between Walshe and Turkish artist and technologist Memo Akten. The result is an uncanny, AI-generated version of Walshe which she can improvise with in real time. For a year, Walshe engaged in a daily ritual of performing solo vocal improvisations in front of her webcam, collecting countless hours of video and audio.

Akten then used this material as the training corpus for a machine learning system he titled GRANNMA MagNet (Granular Neural Music & Audio with Magnitude Networks).

In performance, ULTRACHUNK navigates the hypersphere, generating video and audio in real time. This means that every single frame and sound is generated live, constructed from the fragments of memories in the depths of the neural networks. The original and virtual Walshe inhabit the Uncanny Valley together, singing in duet, improvising, listening and responding to each other.

During the year Walshe spent generating material for the dataset ULTRACHUNK would train on, she kept a journal of the experience. Quotations from her journals are included in the video, which features material from the premiere performance of ULTRACHUNK.

> "**#13:** Companion Species. AI is Companion Species. It is a non-human species humans work alongside and enter into relationships with. It is we humans who are responsible for AI, we humans who need to care for it, shape it, train it."

## 41.5 URSONATE%24 2024

Music album, 45 mins.

# Jennifer Walshe

Kurt Schwitters' *Ursonate* (1922–1932) is considered one of the key texts of Dadaism, and a landmark work in the history of sound poetry. It is a meticulously structured composition, divided into four movements, which stretched to 30 pages of text when Schwitters first published it in his magazine *Merz* in 1932. Walshe has a close relationship with the work, having performed it many times over the last 20 years in a wide variety of contexts. For URSONATE%24, Walshe used AI to generate a new performance of the work, navigating a wide range of genres. She views this as a renewal of both *Ursonate* Dadaism, a century after Schwitters first began working on it.

> "**#1:** Fan Fiction. AI is fan fiction. AI gives fans the power to make more of the music they love, in whatever way they want, regardless of the will of the artists, recording companies or publishers."

## 1 *Polyp*

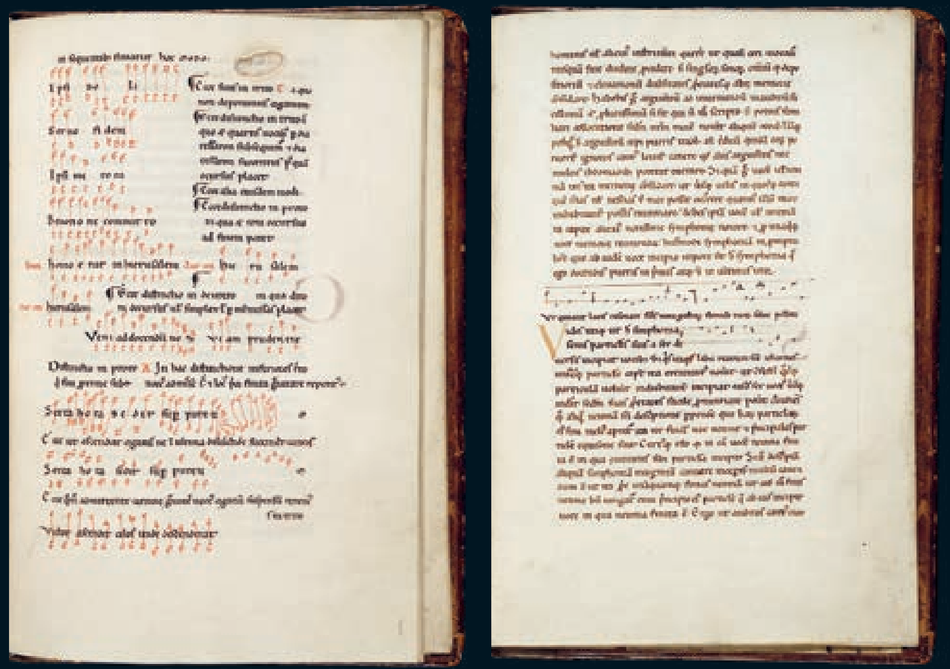
# Marek Poliks & Roberto Alonso Trillo

Image courtesy of Roberto Alonso Trillo & Marek Poliks

# 2.1 *Ut queant laxis & The Guidonian Hand*

16th century copy of the Guidonian Hand, Photo: © Bodleian Libraries, University of Oxford.

# 2.2 *Notations by Guido d'Arezzo*



Left: *Micrologus*. MSR-05, folio 91r, Guido d'Arezzo. Bound with Boethius, De Musica. Alexander Turnbull Library, Wellington, New Zealand. Right: *Epistola ad Michahelem*. MSR-05, folio 99r, Guido d'Arezzo. Bound with Boethius, De Musica. Alexander Turnbull Library, Wellington, New Zealand.

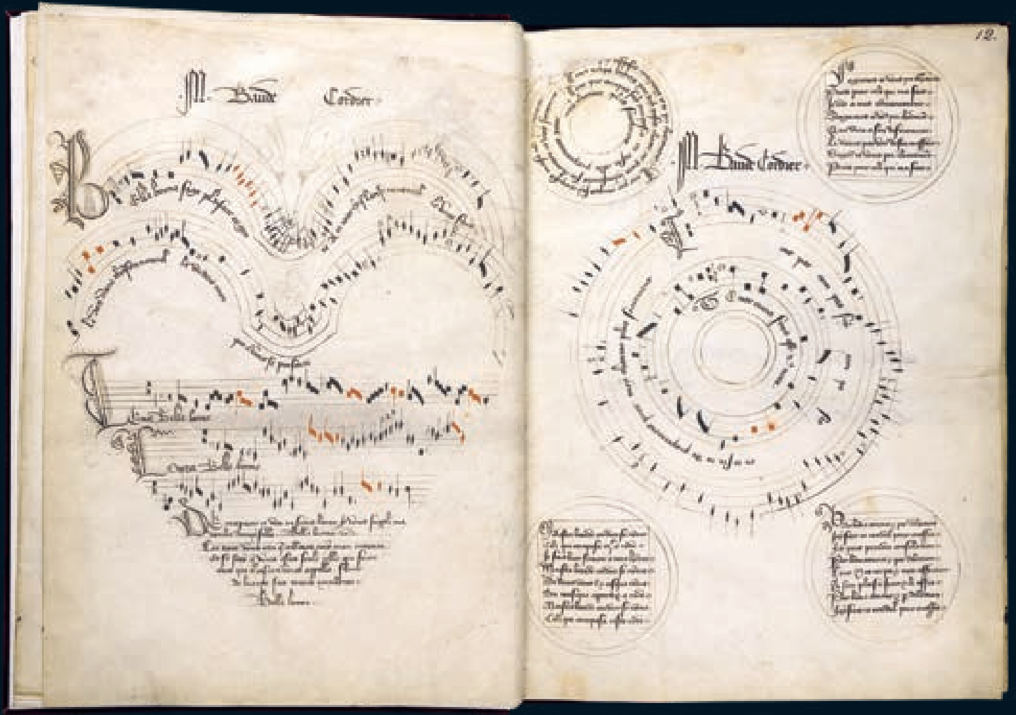
# 3 *Libellus cantus mensurabilis*

## Johannes de Muris

*Libellus cantus mensurabilis* by De Muris. Image courtesy of The Parker Library, Corpus Christi College, Cambridge.

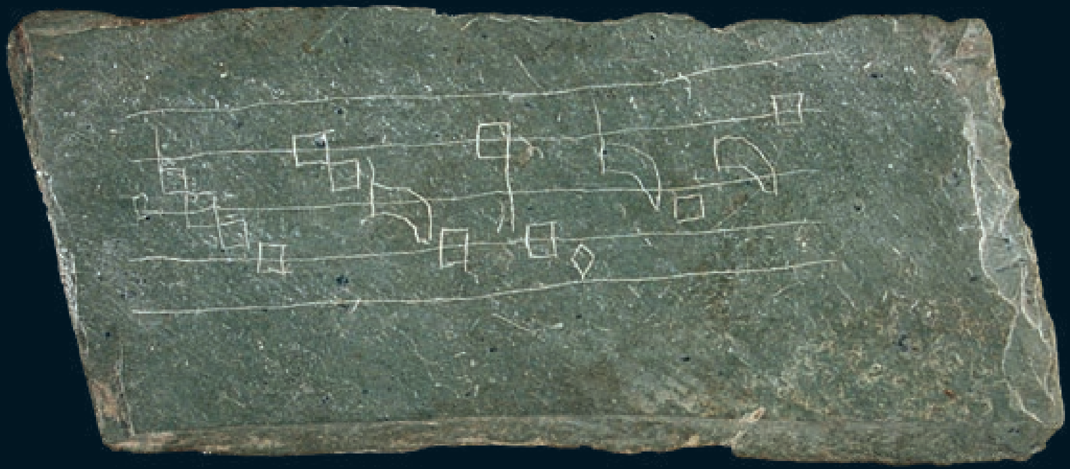
# 4 *Belle, Bonne, Sage – Tout par compas*

## Baude Cordier



Manuscripts of *Belle, Bonne, Sage* (left) & *Tout par compas* (right), by Baude Cordier in the Codex Chantilly.. Courtesy of Château de Chantilly, musée Condé, manuscrit 564, f. 11v. Cliché IRHT-CNRS / Bibliothèque du château de Chantilly. Circular-shaped score of Tout par compas suy compose. Courtesy of Château de Chantilly, musée Condé, manuscrit 564, f. 11v. Cliché IRHT-CNRS / Bibliothèque du château de Chantilly.

# 5 *Polyphony Calculating Slate*



15th century slate with musical notes. Image courtesy of City of Ghent, Urban Archaeology and Heritage Conservation Service.

# 6 *Enigma del Espejo*

## Pedro Cerone


Clue for the Mirror Enigma (left). The Mirror Enigma (right). In *Melopeo y maestro*, Cerone, 1613. World Digital Library.

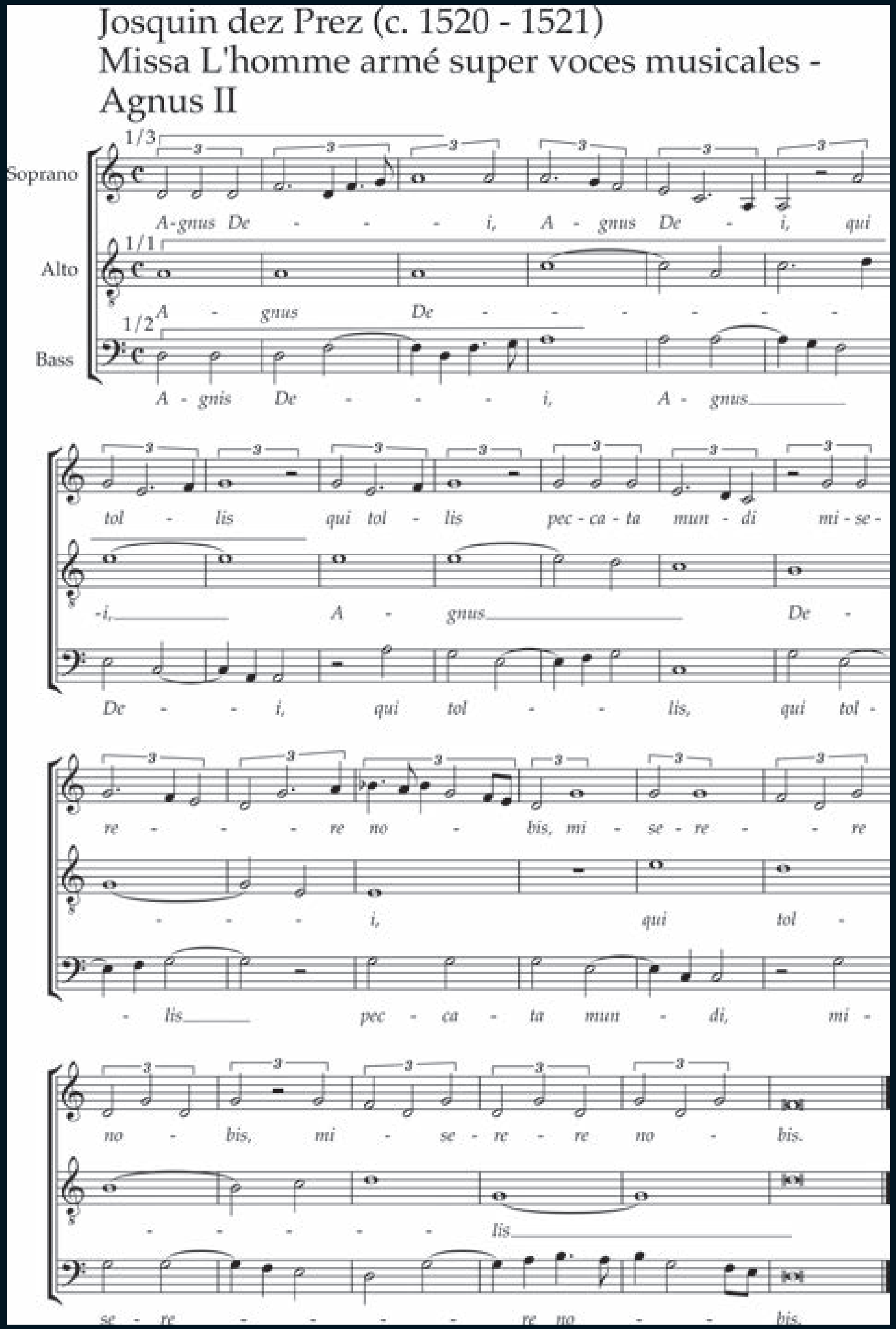
# 7 *Je Missa Di dadi*

## Josquin des Prez

Manuscript of *Missa di dadi*. Digital reproduction. Image courtesy of ÖNB Vienna: SA.77.C.20 /Liber III/Tenor, fol. 28v–29r

# 8 *Missa L'homme armé super voces musicales – Agnus II*

## Josquin des Prez




*Missa L'homme armé super voces musicales – Agnus II*. Courtesy of Jonathan Impett.

# 9 *Six Ways to Represent Music*

## EPFL-DCML

XML encoding for digital representation of Impromptu *No. 3 in G-flat major*, D. 899 (1827) by Franz Schubert. ©DCML.

Original score by Franz Schubert, *Impromptu No. 3 in G-flat major, D. 899* (1827). Courtesy of the Morgan Library & Museum, New York.

## 10.1 *Arca Musarithmica*

## Athanasius Kircher

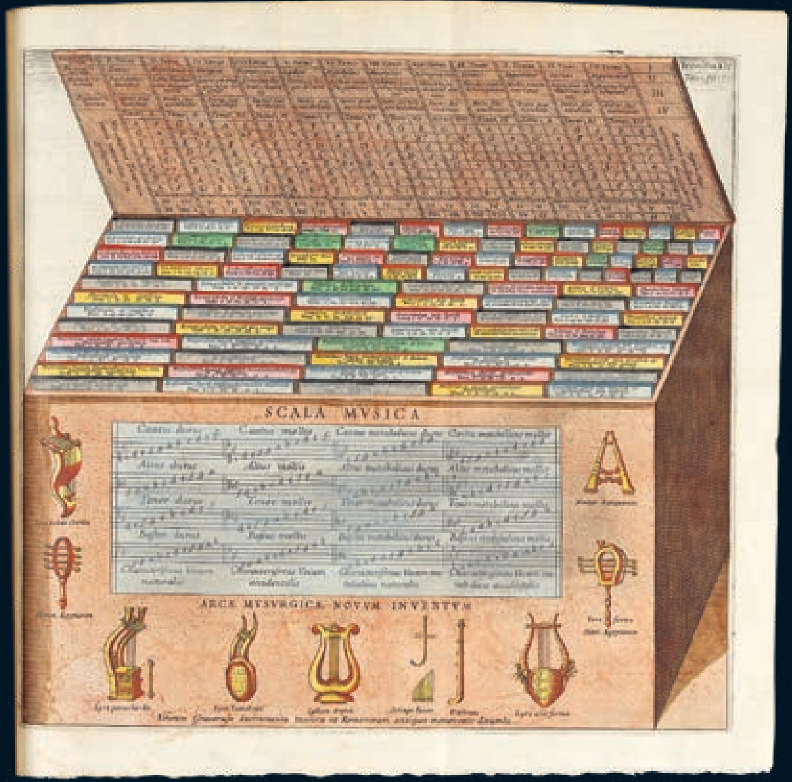



Illustration of the *Arca Musarithmica*. In *Musurgia Universalis* by A. Kircher. Sp Coll Ferguson Af-x.10, by permission of University of Glasgow Archives and Special Collections.

## 10.2 *Neue Hall-und Thon-Kunst*

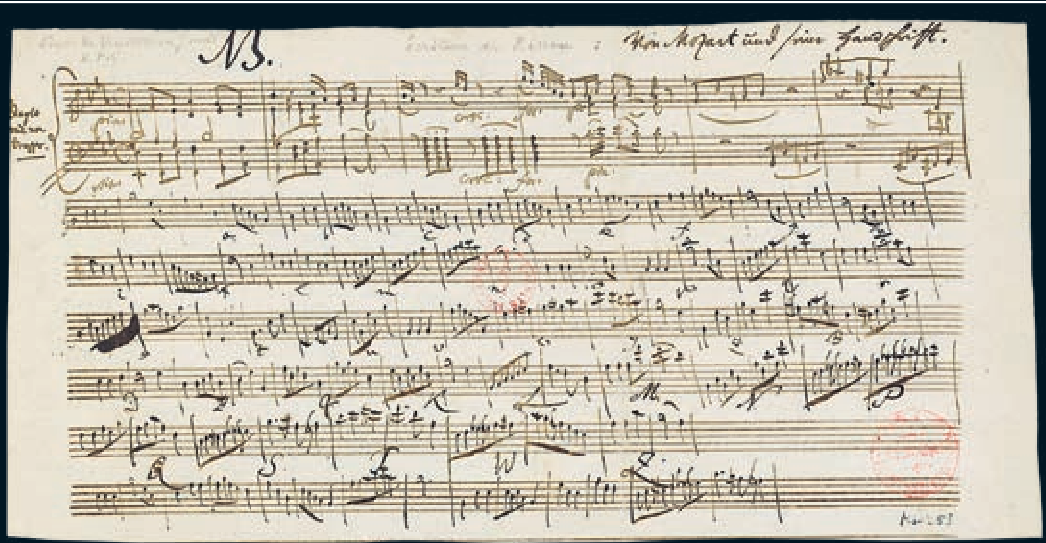
Illustration by A. Kircher. Sp Coll Ferguson Af-x.10, by permission of University of Glasgow Archives and Special Collections.

## 10.3 *Musurgia Universalis*

Illustration of a *hydraulis* organ. In *Musurgia Universalis* by A. Kircher. Sp Coll Ferguson Af-x.10, by permission of University of Glasgow Archives and Special Collections.

## 11 *Musikalisches Würfelspiel*

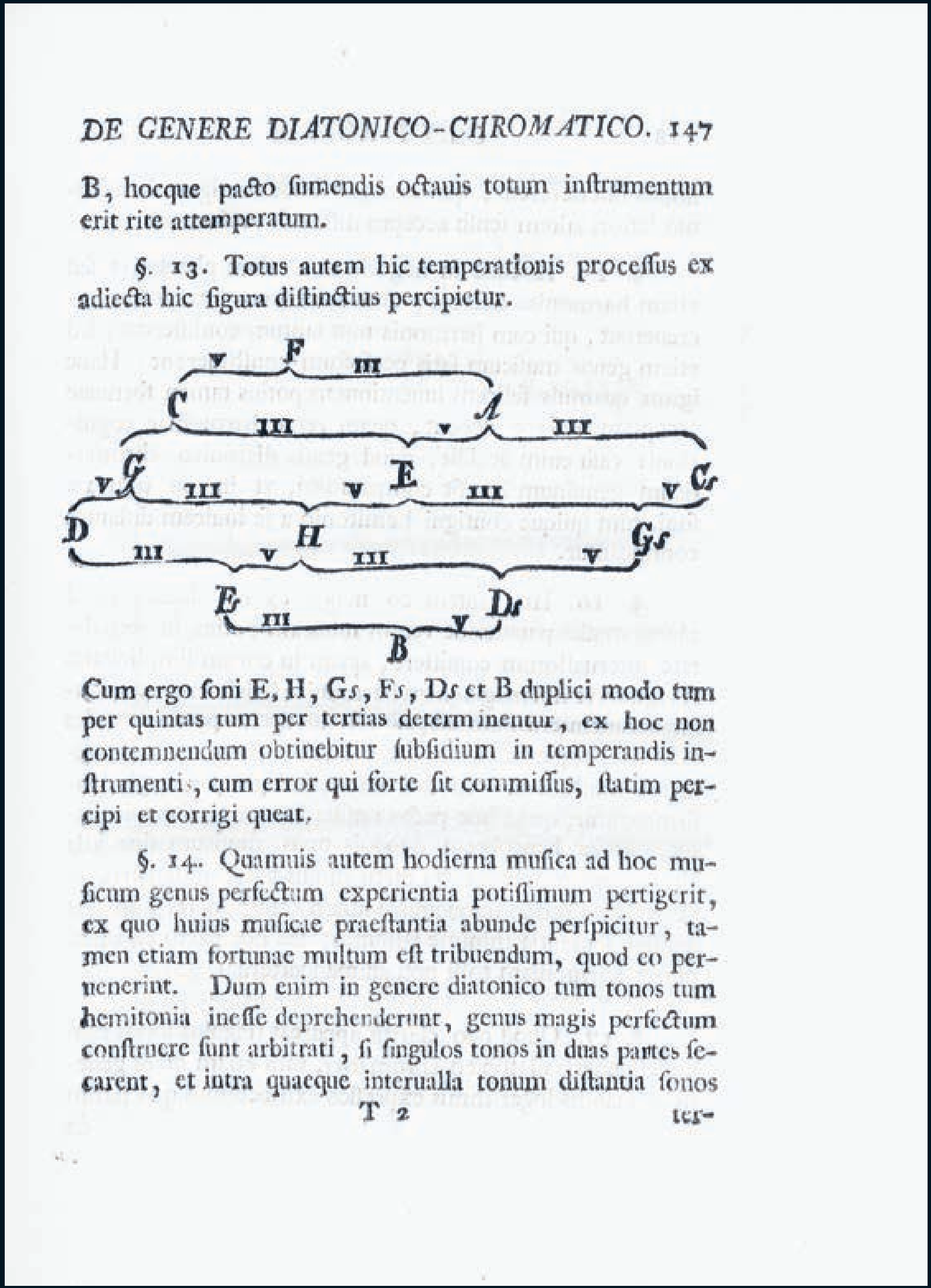
## W. A. Mozart [?]



Digitised score, *Musikalisches Würfelspiel* by W.A. Mozart. Source gallica.bnf.fr / BnF, Music Department, MS-253. Bibliothèque nationale de France.

# 12 *Tentamen novae theoriae musicae*

## Leonhard Euler



DE GENERE DIATONICO-CHROMATICO. 147

B, hocque pacto ſumendis octauis totum inſtrumentum erit rite attemperatum.

§. 13. Totus autem hic temperationis proceſſus ex adiecta hic figura diſtinctius percipietur.

Cum ergo ſoni E, H, Gs, Fs, Ds et B duplici modo tum per quintas tum per tertias determinentur, ex hoc non contemnendum obtinebitur ſubſidium in temperandis inſtrumentis, cum error qui forte ſit commiſſus, ſtatim percipi et corrigi queat.

§. 14. Quamuis autem hodierna muſica ad hoc muſicum genus perfectum experientia potiſſimum pertigerit, ex quo huius muſicae praeſtantia abunde perſpicitur, tamen etiam fortunae multum eſt tribuendum, quod eo peruenerint. Dum enim in genere diatonico tum tonos tum hemitonia ineſſe deprehenderunt, genus magis perfectum conſtruere ſunt arbitrati, ſi ſingulos tonos in duas partes ſecarent, et intra quaeque interualla tonum diſtantia ſonos

T 2 ter-

"Tonnetz" developed by Euler in his treatise, *Tentamen novae theoriae musicae*. Courtesy of ETH-Bibliothek Zürich.

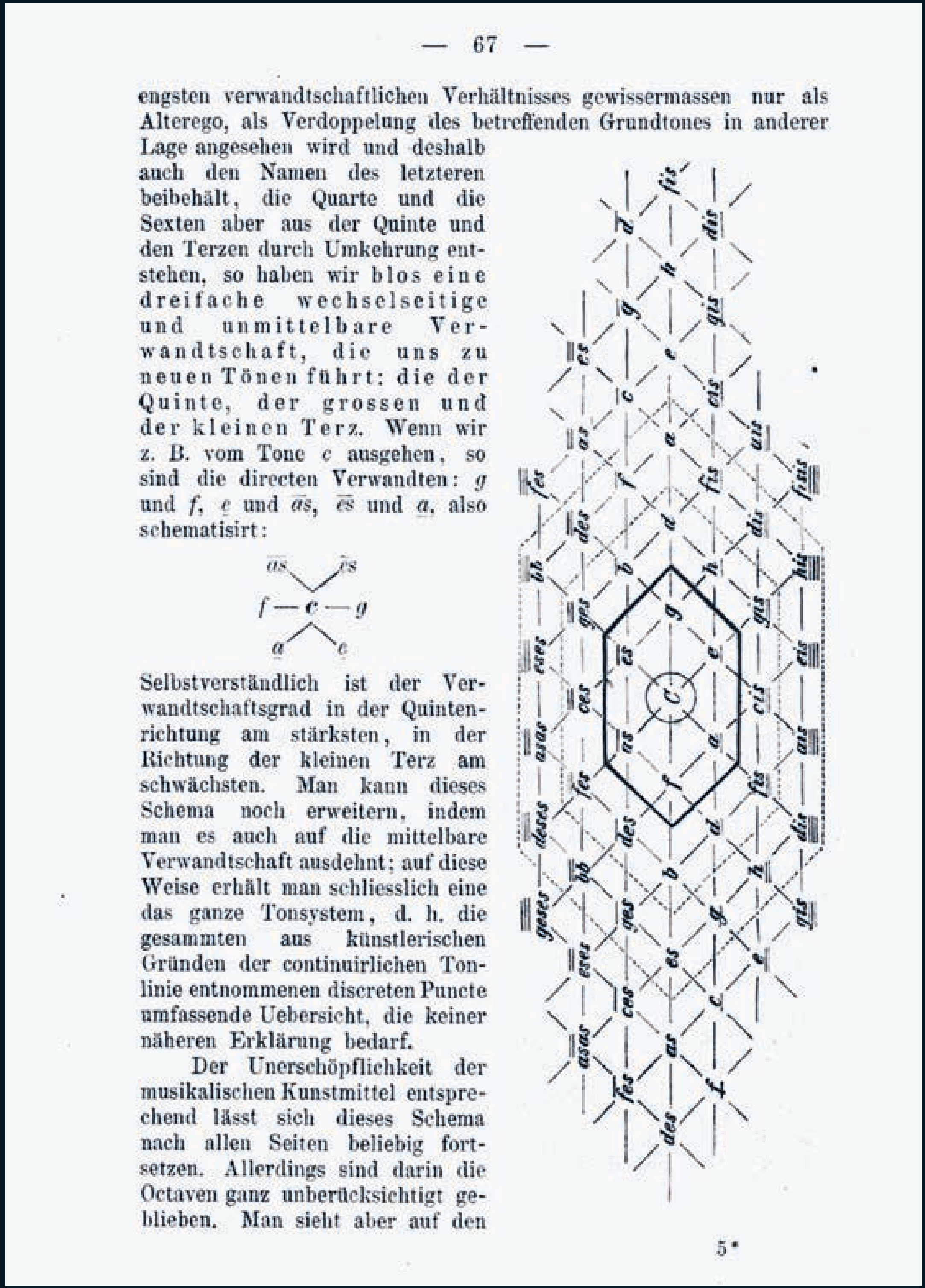
# 13 *Circle of Fifths*

## Nikolay Diletsky

Digital reproduction of Diletsky's Circle of Fifth. Image courtesy of the New York Public Library.

## 14 *Die Lehre von den musikalischen Klängen*

# Otakar Hostinsky



— 67 —

engsten verwandtschaftlichen Verhältnisses gewissermassen nur als Alterego, als Verdoppelung des betreffenden Grundtones in anderer Lage angesehen wird und deshalb auch den Namen des letzteren beibehält, die Quarte und die Sexten aber aus der Quinte und den Terzen durch Umkehrung entstehen, so haben wir blos eine dreifache wechselseitige und unmittelbare Verwandtschaft, die uns zu neuen Tönen führt: die der Quinte, der grossen und der kleinen Terz. Wenn wir z. B. vom Tone *c* ausgehen, so sind die directen Verwandten: *g* und *f*, *e* und $\overline{as}$, $\overline{es}$ und *a*, also schematisirt:

$$\begin{array}{ccccc} & \overline{as} & & \overline{es} & \\ f & — & c & — & g \\ & a & & e & \end{array}$$

Selbstverständlich ist der Verwandtschaftsgrad in der Quintenrichtung am stärksten, in der Richtung der kleinen Terz am schwächsten. Man kann dieses Schema noch erweitern, indem man es auch auf die mittelbare Verwandtschaft ausdehnt; auf diese Weise erhält man schliesslich eine das ganze Tonsystem, d. h. die gesammten aus künstlerischen Gründen der continuirlichen Tonlinie entnommenen discreten Puncte umfassende Uebersicht, die keiner näheren Erklärung bedarf.

Der Unerschöpflichkeit der musikalischen Kunstmittel entsprechend lässt sich dieses Schema nach allen Seiten beliebig fortsetzen. Allerdings sind darin die Octaven ganz unberücksichtigt geblieben. Man sieht aber auf den

5*

Musical network by O. Hostinsky, in *Die Lehre von den musikalischen Klängen*. Digital reproduction from the New York Public Library. Originally published by H. Dominicus, Prague, 1879.

## 15 *12-part Colour-Sound Circle*

# Josef Matthias Hauer

J. M. Hauer's 12-Tone Colour Circle. Image courtesy of mumok – Museum moderner Kunst Stiftung Ludwig Wien, Sammlung Dieter und Gertraud Bogner im mumok. Photo © mumok.

## 16 *Coltrane's Circle*

# John Coltrane

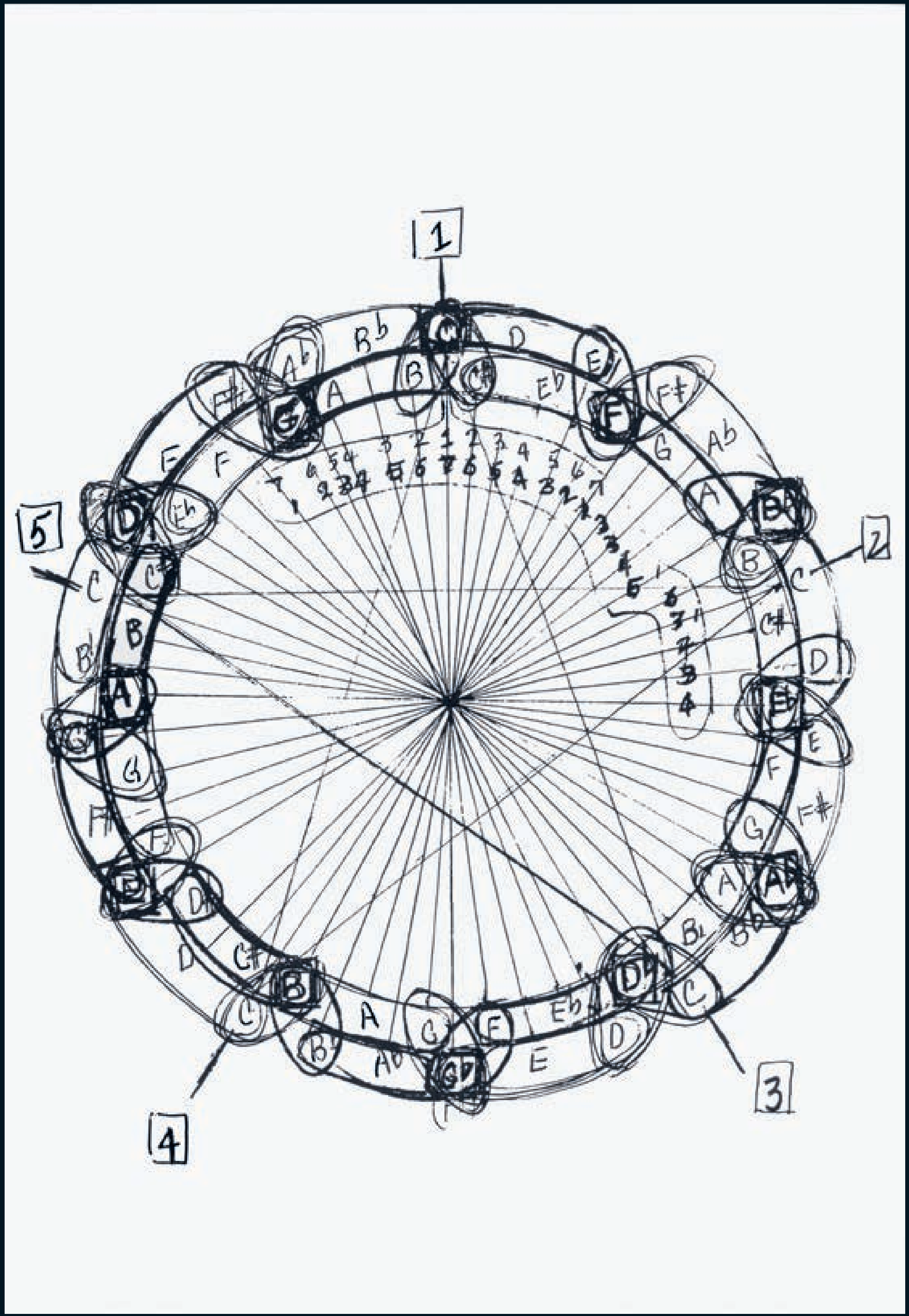
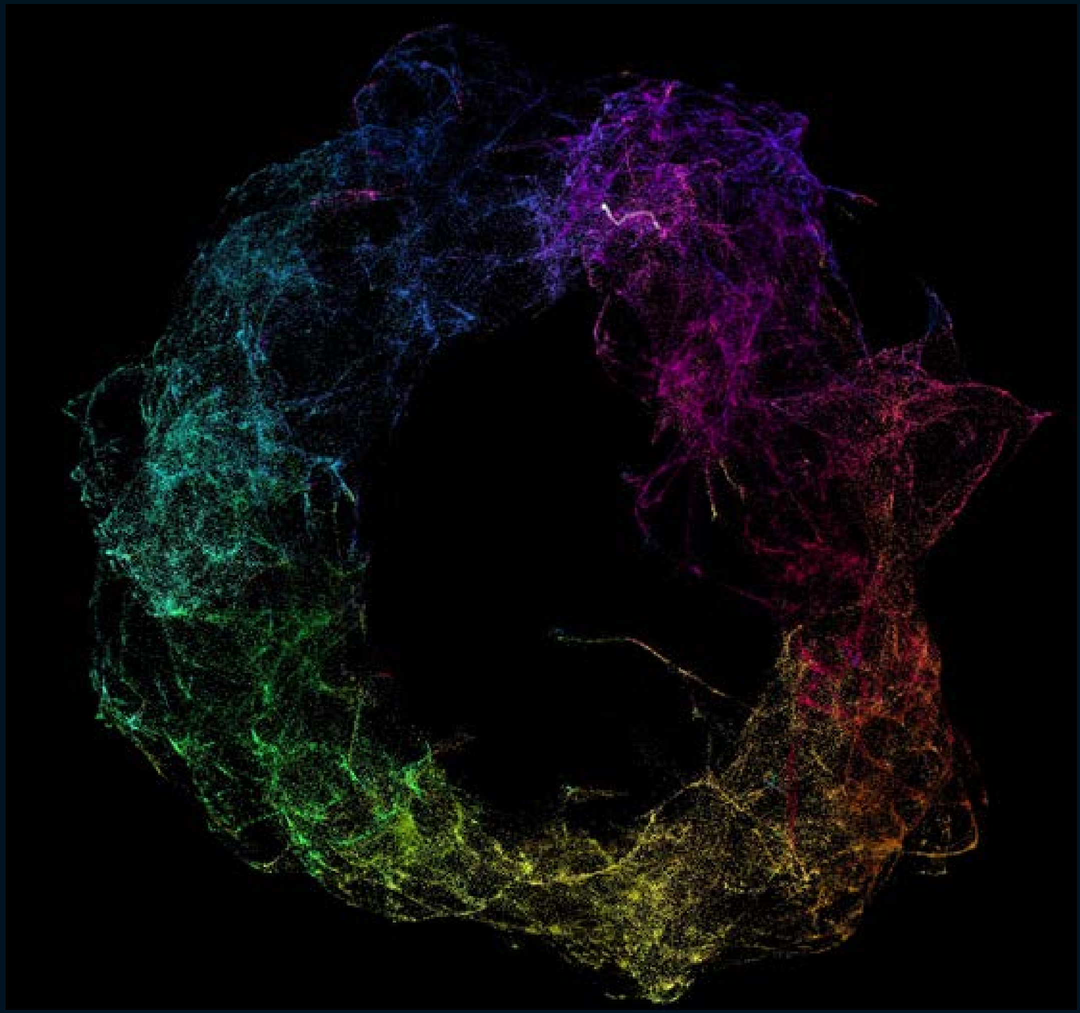



Diagram of Coltrane's Circle, from Yusef Lateef, 1981, Repository of Scales and Melodic Patterns. Jamey Aebersold Jazz.

## 17 *Four Perspectives on Structure in Music*

# EPFL-DCML

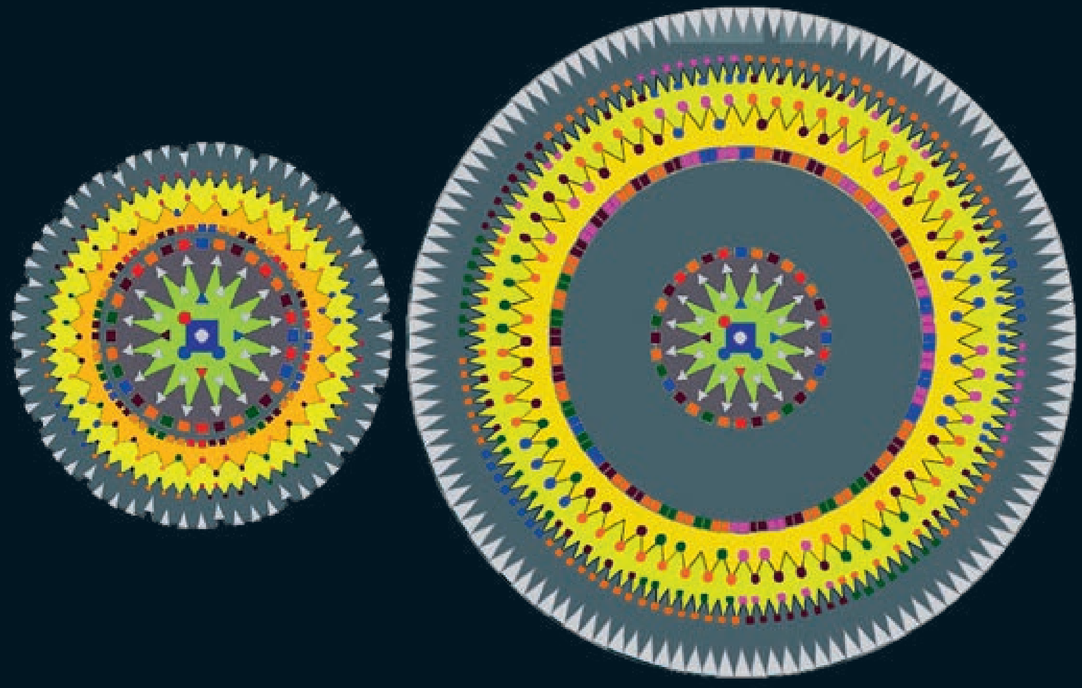


The Tonal Cloud in the shape of a torus.©DCML.

# 18.1 *Gamelan*

Balinese metallophone. Musée d'ethnographie de Genève (MEG). ©Jonathan Watts.

# 18.2 *Digital Gamelan*



Javanese Gamelan, *Ladrang*, ratios 1 & 2. ©Kati Basset.

# 19 *Polyrhythms in Central African Music*

Polyphonic singing of the Aka Pygmies of Central Africa (Central African Republic). ©Commission nationale Centrafricaine et Ministère de la jeunesse et des sports, arts et culture. Source: UNESCO, https://ich.unesco.org/en/RL/polyphonic-singing-of-the-aka-pygmies-of-central-africa-00082.

# 20 *Scalar Expansion in North Indian Classical Music*

## Martin Rohrmeier and Richard Widdess

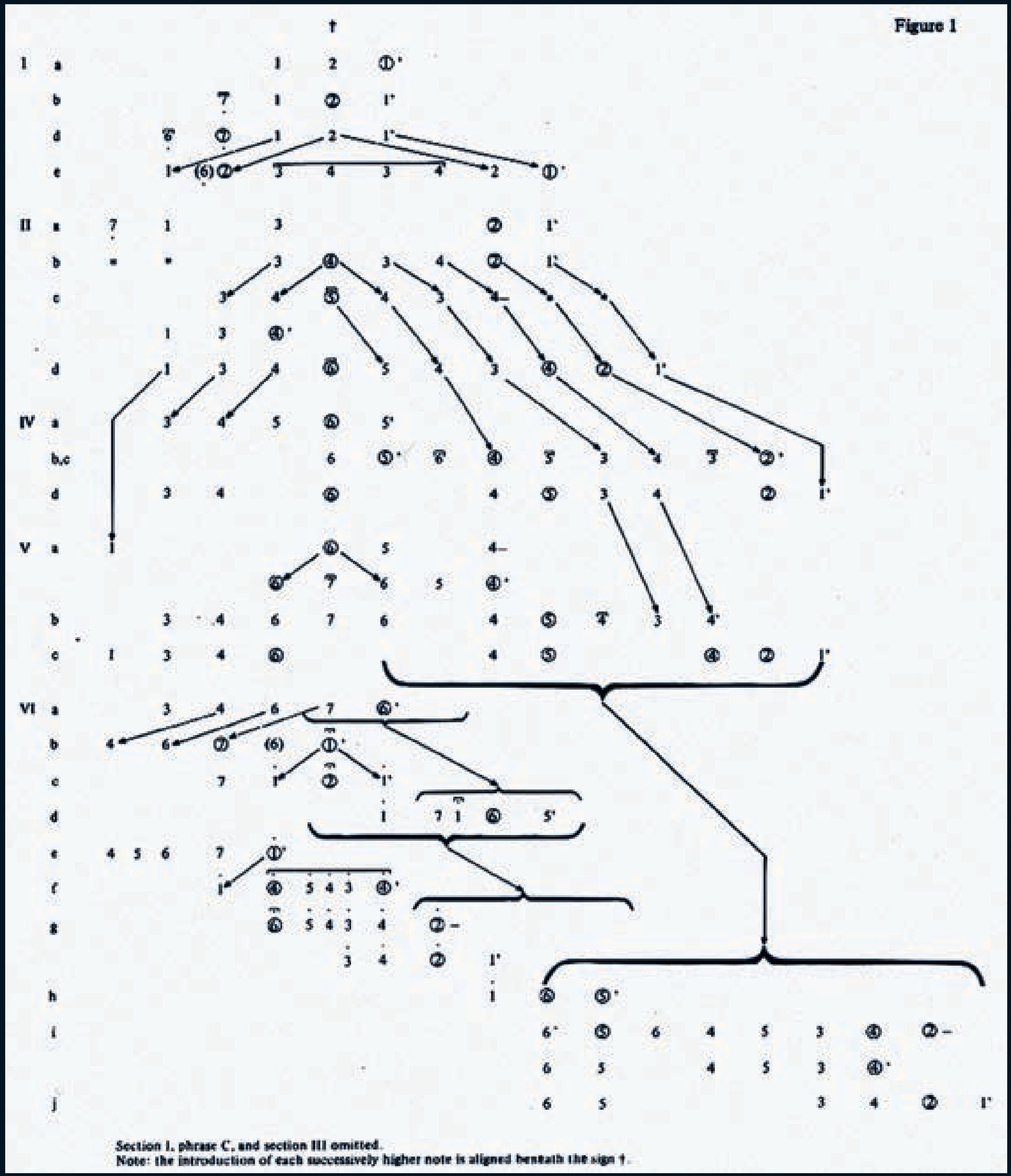



Diagram of the Scalar Expansion Principle, in *Music & Tradition, Essays on Asian and other musics presented to Laurence Picken*, edited by D.R. Widess & R.F. Wolpert, Cambridge University Press, 1981. Courtesy of Richard Widdess.

# 21 *Persian Automaton*

12th century Persian automaton. Image courtesy of the National Museum of Asian Art, Smithsonian Institution, Freer Collection, Purchase—Charles Lang Freer Endowment, F1930.73.

# 22 *The Musician*

## Henri-Louis Jaquet-Droz

The Musician. ©Musée d'art et d'histoire de Neuchâtel (Switzerland). Photo: Stefano Iori.

*The Musician* playing on the piano ©Musée d'art et d'histoire de Neuchâtel (Switzerland). Photo: Stefano Iori.

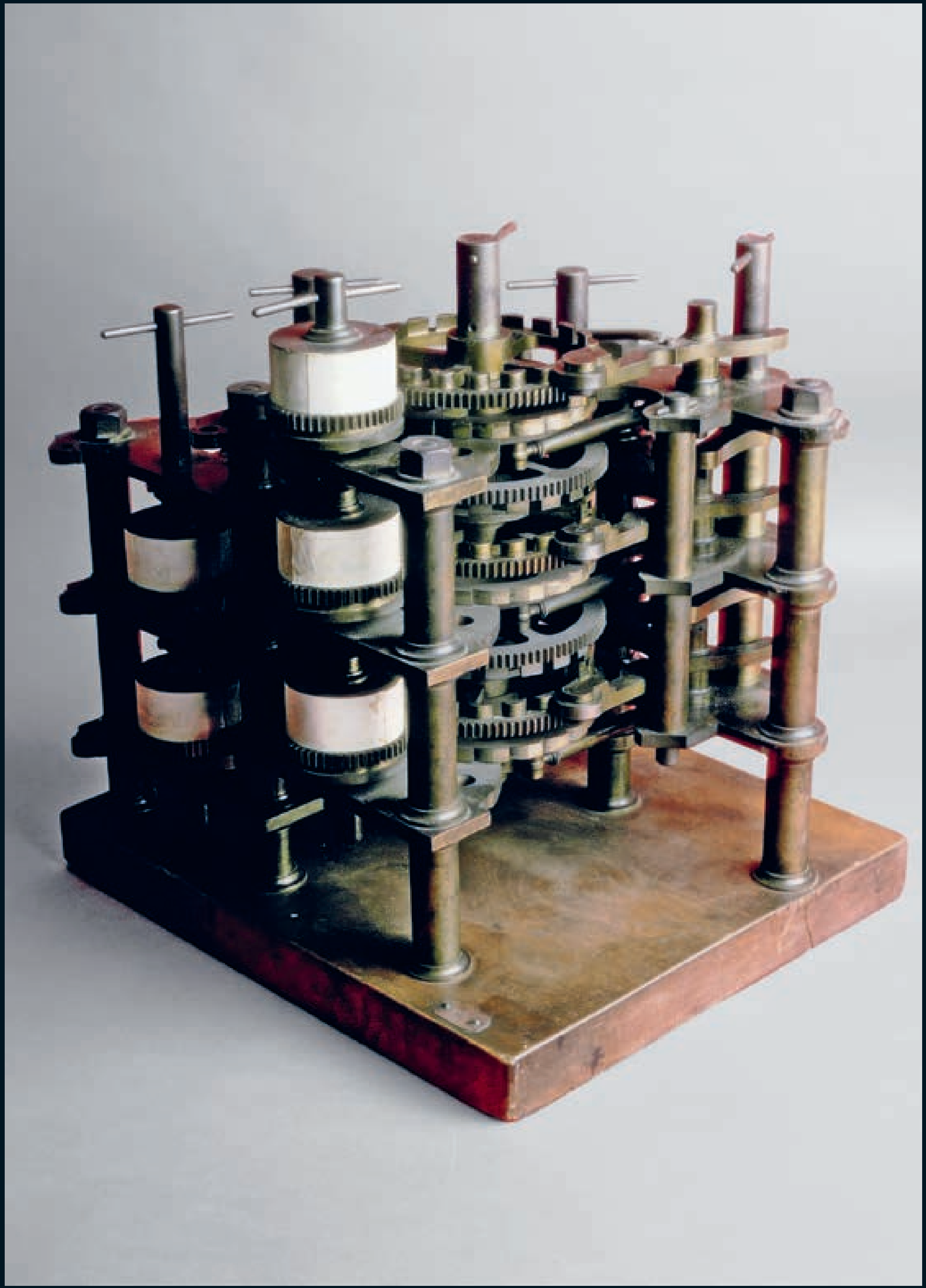
Internal mechanism of *The Musician*. ©Musée d'art et d'histoire de Neuchâtel (Switzerland). Photo: Stefano Iori.

# 23 *Angel with Harp Automaton*

Angel with harp automaton. Image courtesy of Museum für Musikautomaten Seewen.

## 24 *Portion of the Babbage Difference Engine No. 1*

## Charles Babbage



Portion of the Babbage Difference Engine No.1. Image courtesy of the Whipple Museum of the History of Science, University of Cambridge.

## 25 *Ada Lovelace's Notes*

## Ada Lovelace

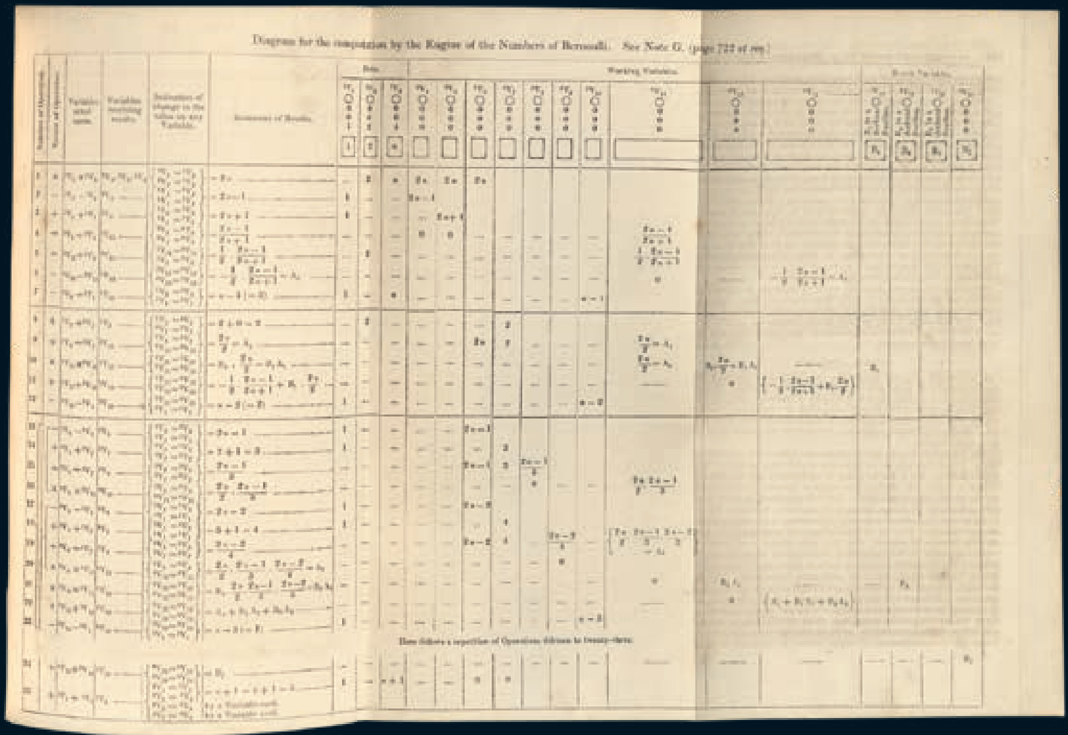


Diagram for the computation by the Engine of the Numbers of Bernoulli. See Note G. (page 722 et seq.)

Foldout diagram from Lovelace's notes. By permission of the Master and Fellows of St John's College, Cambridge.

Portrait of Ada, Countess of Lovelace. This image is released under CC BY-NC-SA 4.0 Licence. © The Board of Trustees of the Science Museum, London.

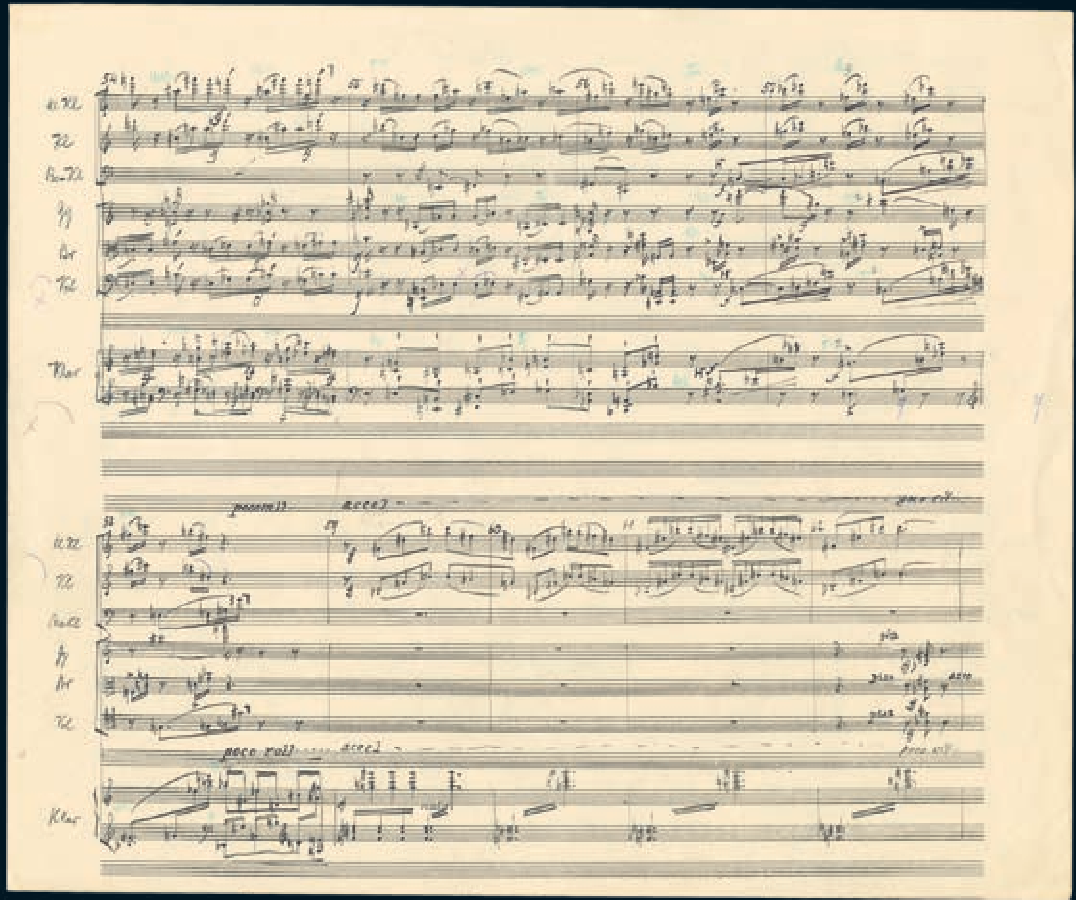
# 26 Arnold Schönberg


Arnold Schönberg and his wife. ©Arnold Schönberg Center, Vienna.

Portrait of Arnold Schönberg. ©Arnold Schönberg Center, Vienna.

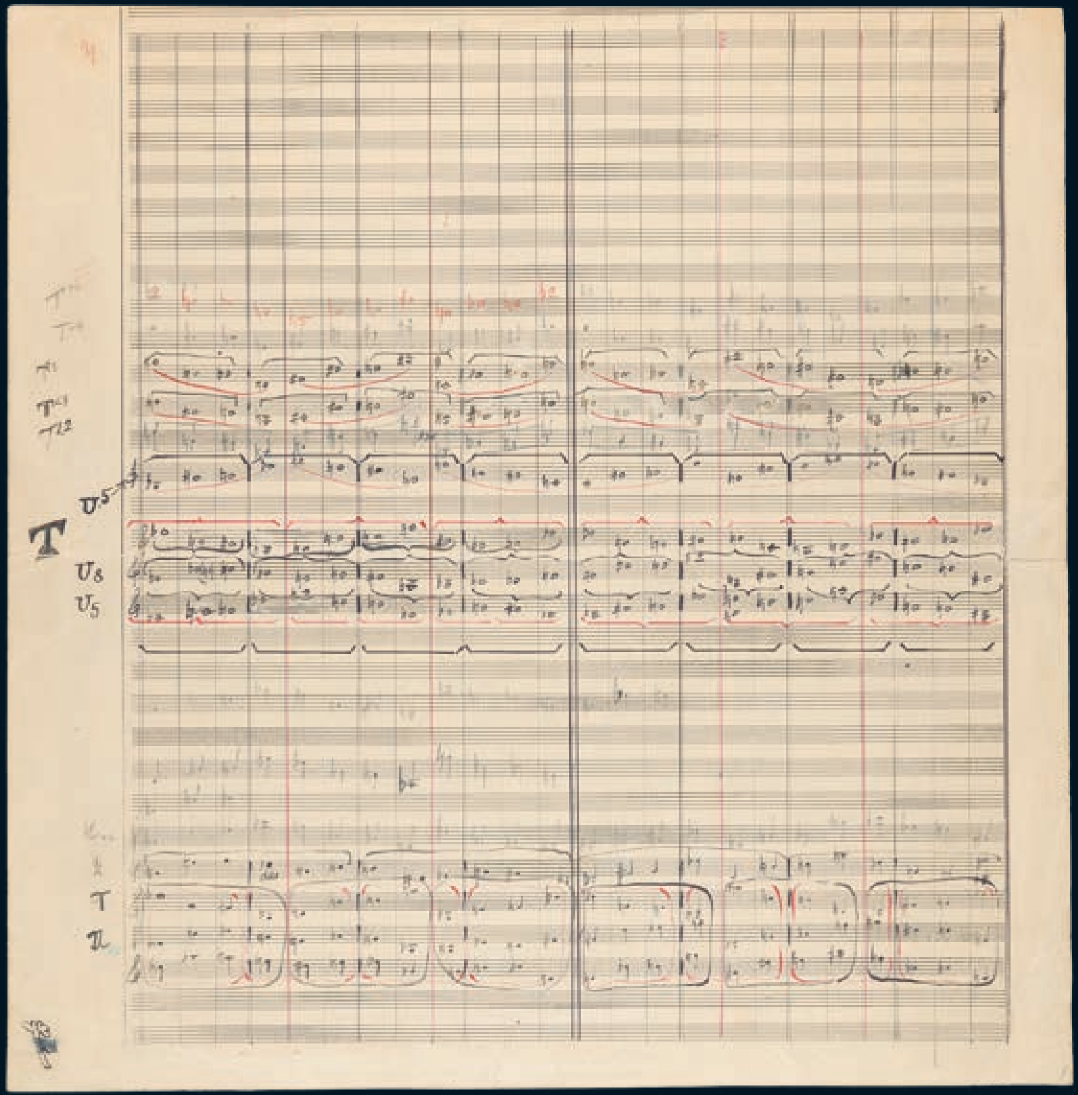
# 26.1 *Suite op. 29, Score Movement 1 (Ouverture. Allegretto)*

## Arnold Schönberg



*Suite op.* 29, Score, MS29, 1119. ©Arnold Schönberg Center, Vienna.

# 26.2 *Suite op. 29, Twelve-tone row chart*

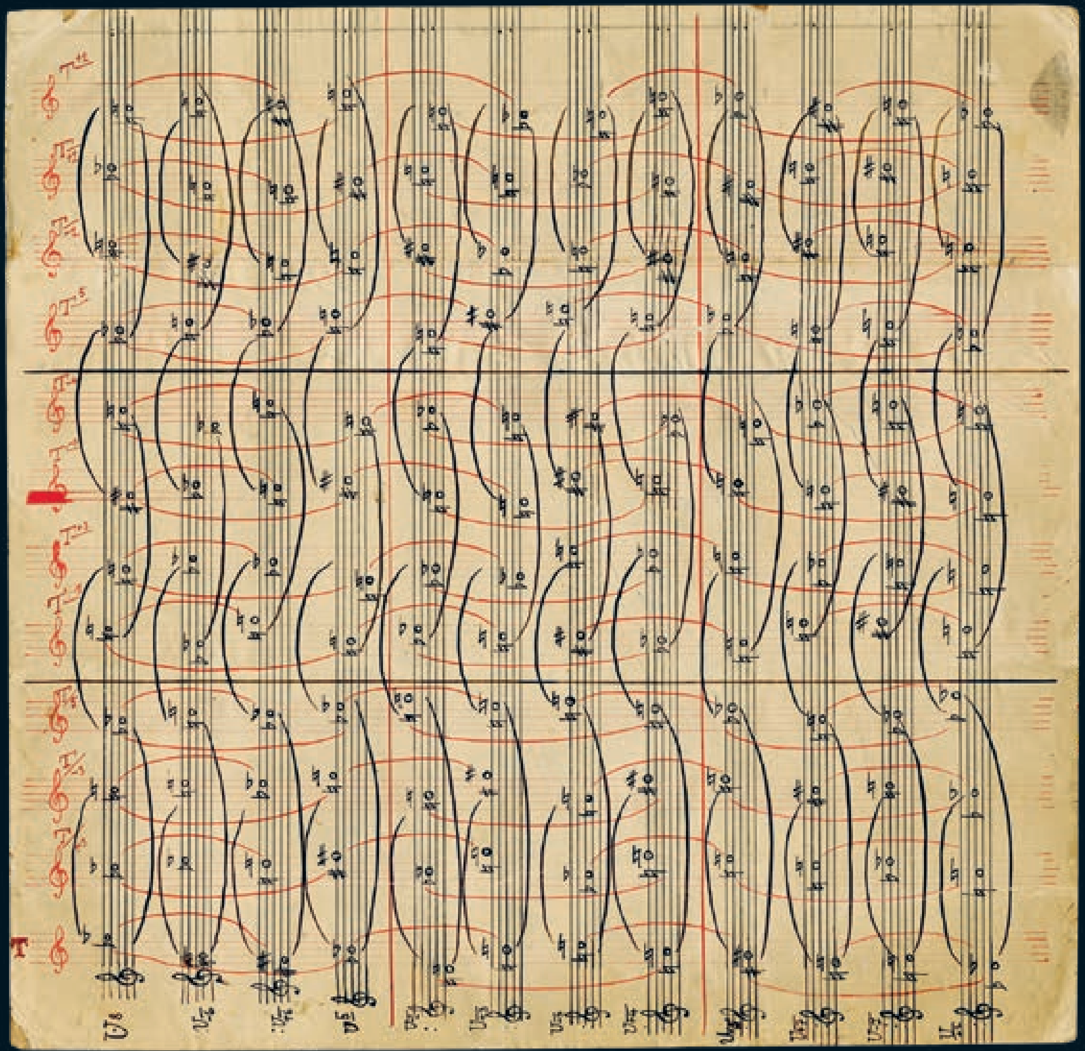


*Suite op. 29*, Twelve-tone row chart, MS29, 1181. ©Arnold Schönberg Center, Vienna.

# 26.3 *Suite op. 29, Twelve-tone row chart*

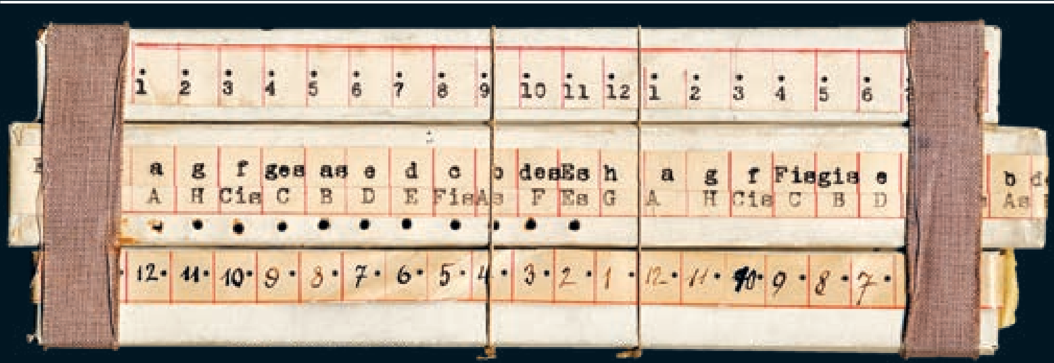
*Suite op. 29*, Twelve-tone row chart, MS29, 1171 ©Arnold Schönberg Center, Vienna.

# 26.4 *Suite op. 29, Bidirectional twelve-tone row chart*



*Suite op. 29*, Bidirectional twelve tone row chart, MS29. ©Arnold Schönberg Center, Vienna.

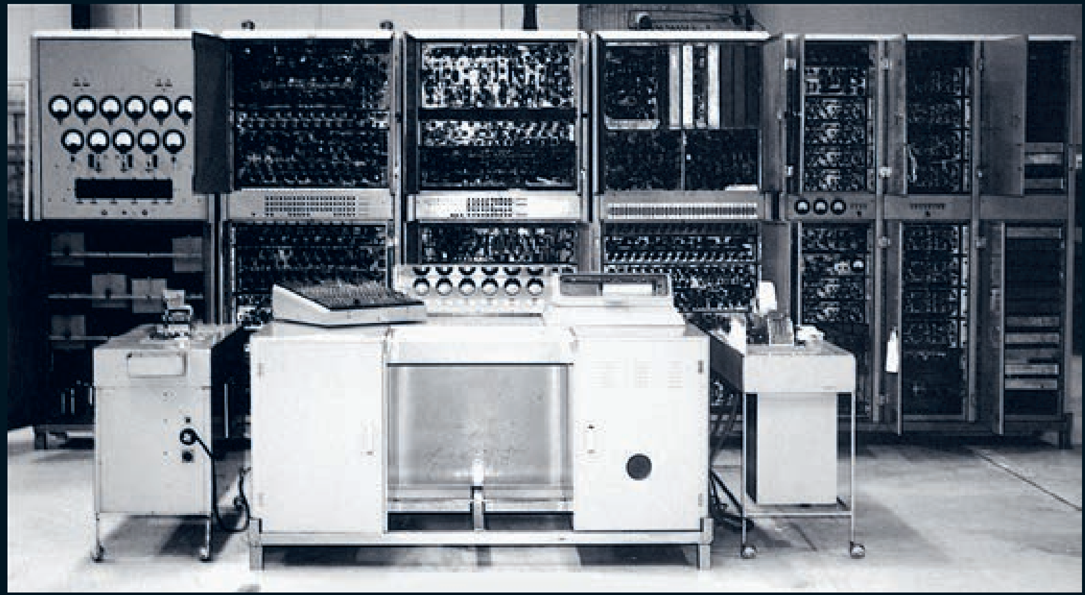
# 26.5 *Wind Quintet, op. 26, Twelve-tone row ruler*




*Wind Quintet, op. 26*, Twelve-tone row ruler, MS26. ©Arnold Schönberg Center, Vienna.

# 27.1 *CSIRAC computer*

## Maston Beard, Trevor Pearcey & Geoff Hill



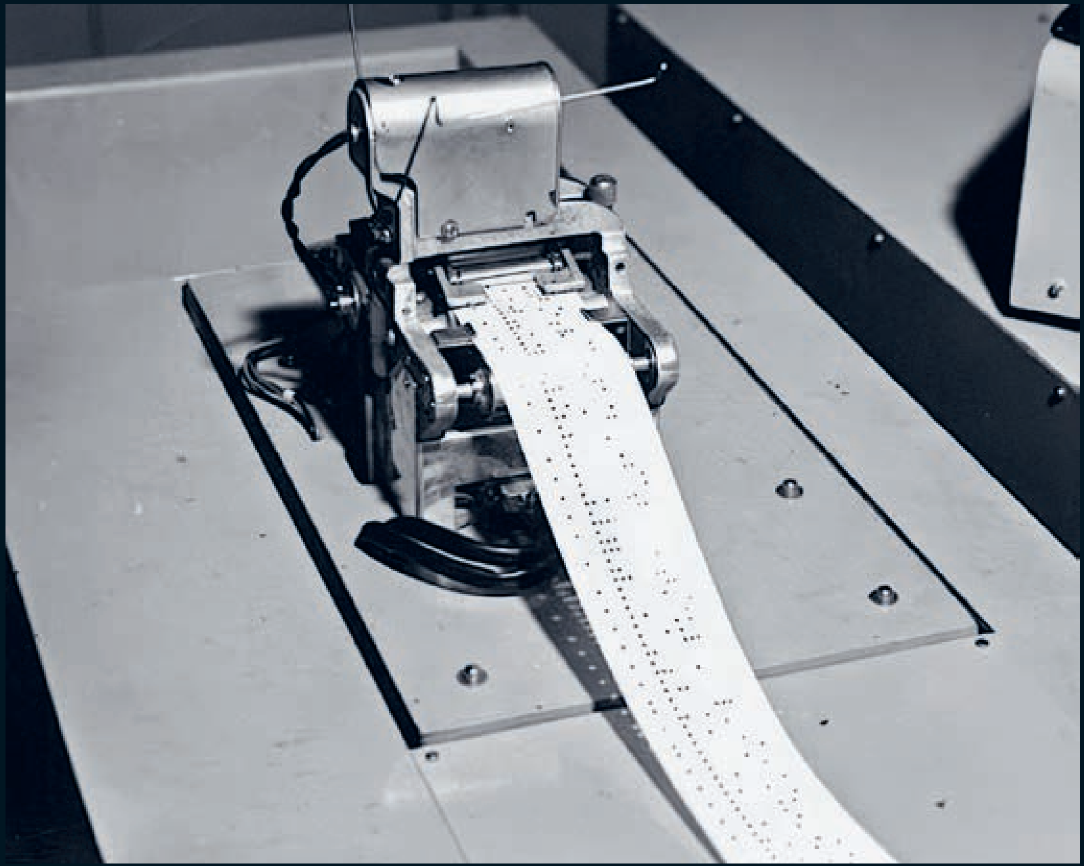
Full view of CSIRAC. Photo: Paul Doornbusch, with kind permission.

CSIRAC being operated by Geoff Hill & Trevor Pearcey. ©CSIRO Archive.

Jurij Semkiw operating CSIRAC. ©CSIRO Archive.

# 27.2 *CSIRAC Computer* Programme Tape

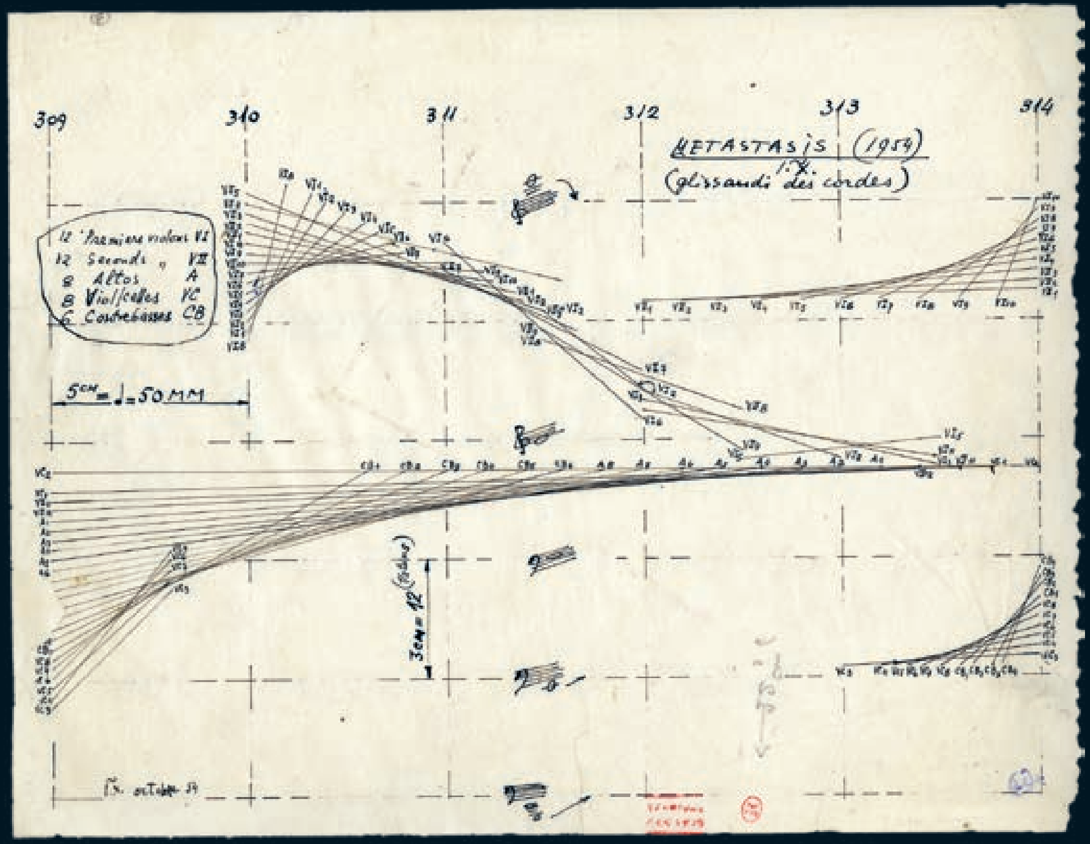
## Geoff Hill

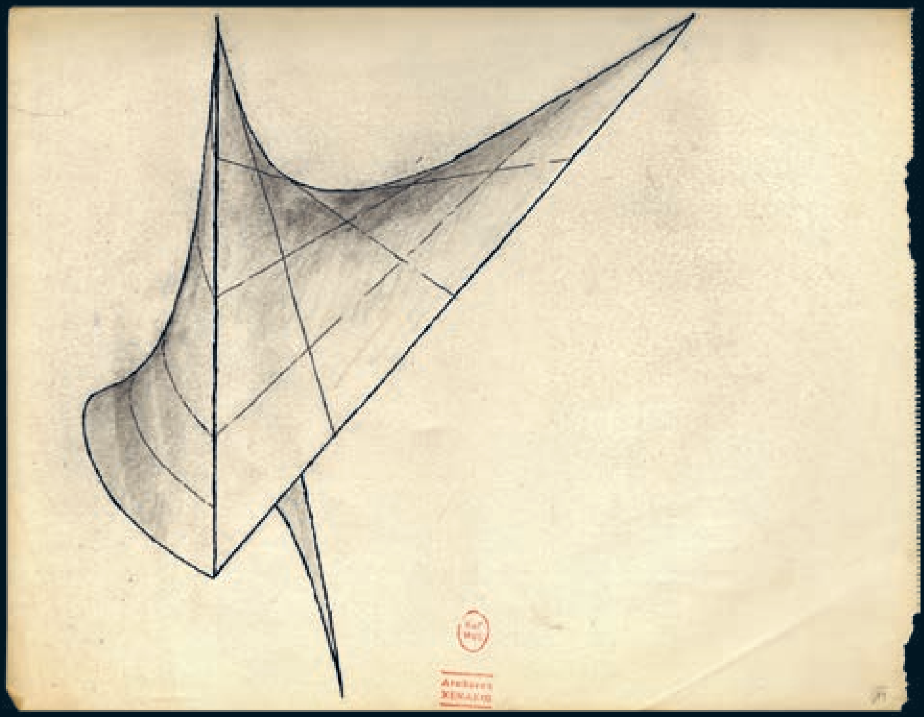


Computer programme used for CSIRAC. Image courtesy of CSIRO Archive.

# 28.1 *Xenakis Archives*

## Iannis Xenakis



Graphic material for musical composition on UPIC. Courtesy of the Iannis Xenakis family.

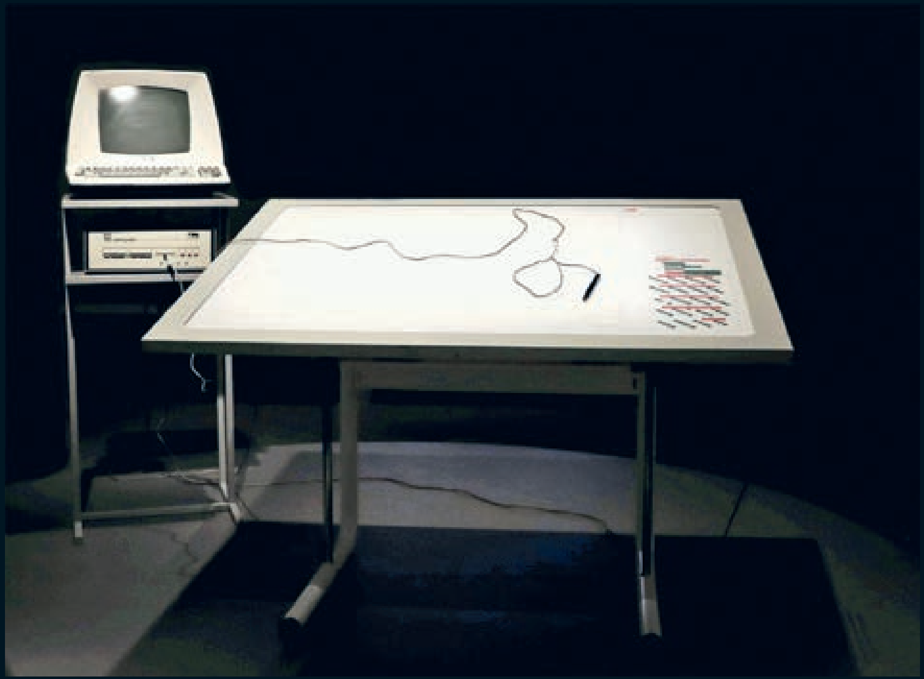
## 28.2 *Philips Pavilion, Expo 58*

## Iannis Xenakis & Le Corbusier

Philips pavillion at Expo 58. Under Creative Commons Attribution license.

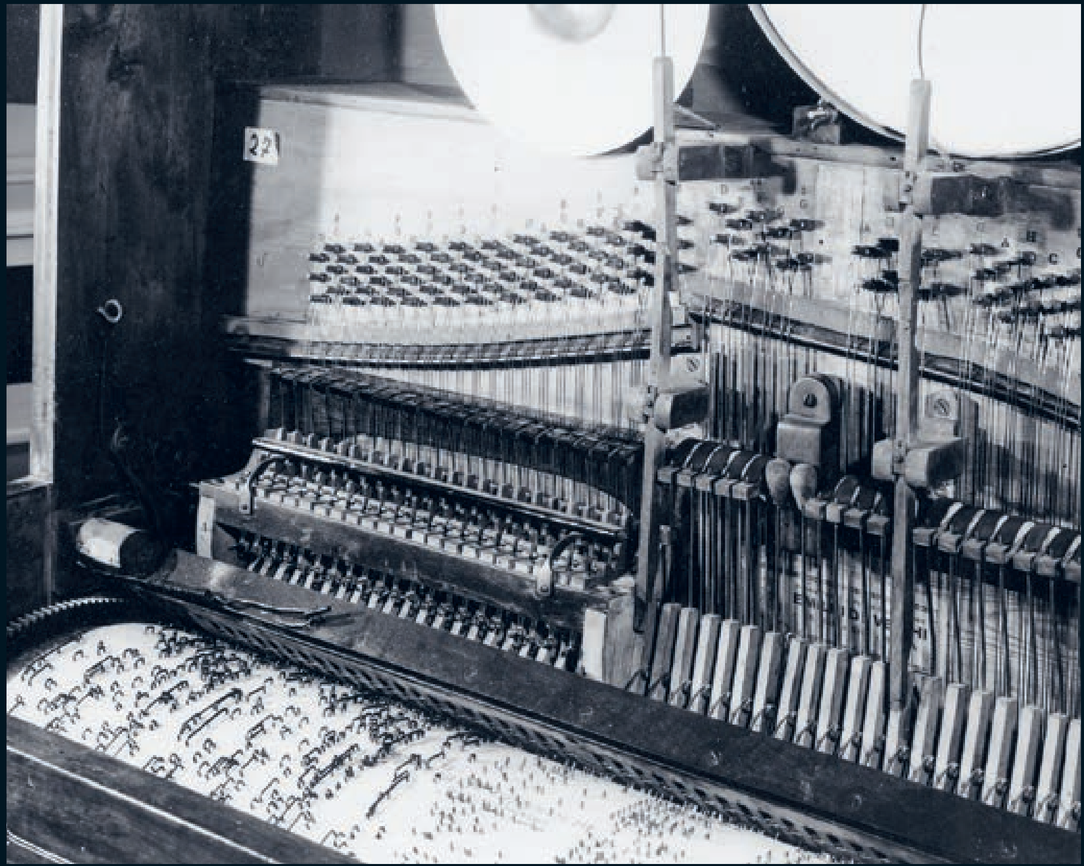
## 28.3 *UPIC*

## Iannis Xenakis



*UPIC*. Courtesy of CMRC/KSYME, Athens. © Estela Valasi.

## 29 Player Piano Music



Old mechanical piano. ©Alamy Stock Photo.

Yamaha C6 Disklavier. ©Yamaha.

## 29.1 *Study 41B*

## Conlon Nancarrow

Nancarrow using a hand-punching machine for piano rolls, 1981. © Philip Makanna. Courtesy Eva Soltes.

## 29.2 *Étude 14A*

## György Ligeti

Ligeti in his study, 1982. ©Peter Andersen. György Ligeti Collection, Paul Sacher Foundation, Basel.

## 29.3 *Voyager*

## George Lewis

Lewis with an Apple II & an algorithmically-driven kalimba instrument. Image courtesy of George Lewis.

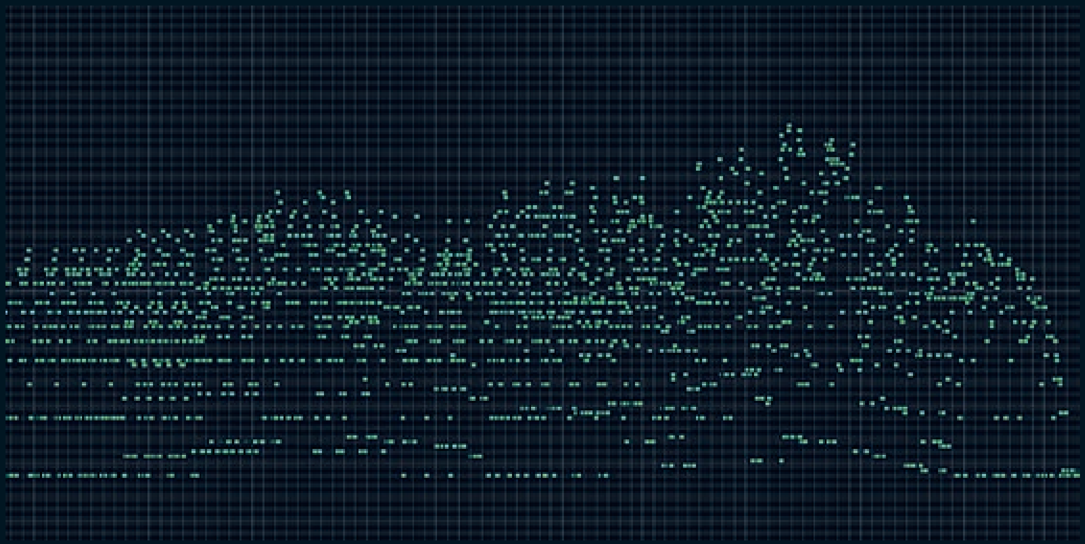
## 29.4 *OTOdeBLU*

## Clarence Barlow


Clarence Barlow with George Lewis. Image courtesy of Birgit Faustmann.

## 29.5 *Continuity 4*

## Paul Doornbusch



*Continuity 4* structure. Image courtesy of Paul Doornbusch.

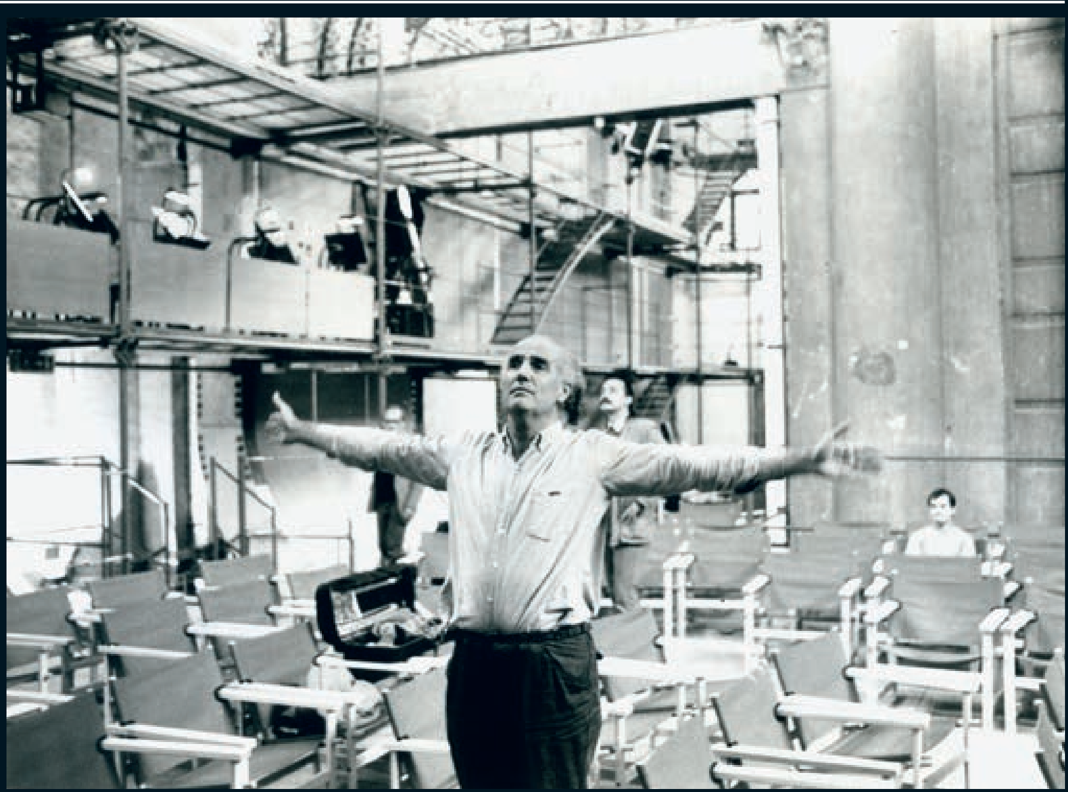
## 29.6 *Arabesque*

## Nicolas Namoradze

Portrait of Nicolas Namoradze. ©Tina Krohn.

## 30.1 *Prometeo. Tragedia dell'ascolto*

## Luigi Nono

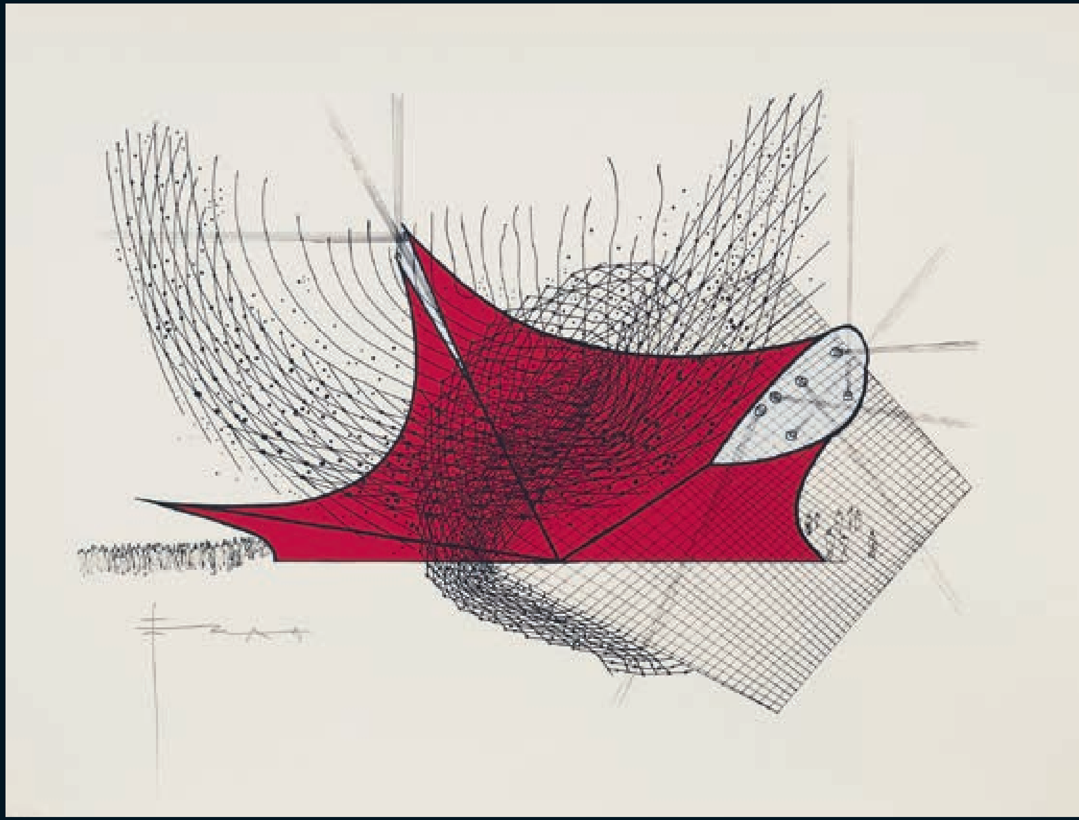


The composer Luigi Nono during rehearsals for the premiere of *Prometeo*, 1984. © Archivio Storico della Biennale di Venezia-ASAC / Photographer: Lorenzo Capellini.

Architectural structure of *Prometeo*, designed by Renzo Piano. © Archivio Storico della Biennale di Venezia-ASAC / Photographer: Lorenzo Capellini.

## 30.2 *La Légende d'Eer*

## Iannis Xenakis



Sketch of the Diatope, by Iannis Xenakis. Image courtesy of the Iannis Xenakis Family.

The Diatope outside of the Centre Georges Pompidou in Paris. Image credit: ©Bruno Rastoin.

Performance of *La Légende d'Eer* in the Diatope. Image credit: ©Bruno Rastoin.

Performance of *La Légende d'Eer* in the Diatope. Image credit: ©Bruno Rastoin.

## 31 *Studie II*

## Karlheinz Stockhausen

WDR studio used by Stockhausen.©WDR / Volker Müller.

Portraits of Stockhausen at the WDR studio. ©WDR.

## 32 *Fontana Mix*

## John Cage

John Cage in a recording studio (c.1972). Photographer: ©James Klosty. Courtesy of the John Cage Trust.

## 33 *Revox 36G*

Revox 36G. Courtesy of SMEM. Photo: ©Victorien Genna.

## 34 *Buchla 200e Skylab*

The Buchla 200e Skylab synthesiser. Courtesy of SMEM. Photo: ©Victorien Genna.

## 35 *Expert Senior Gramophone*

Expert Senior Gramophone. Private collection.

## 36 *The Hands*

# Michel Waisvisz

Michel Waisvisz performing with *The Hands*. Archives Michel Waisvisz.

## 37 *Lady's Glove v.4*

# Laetitia Sonami

Laetitia Sonami with the *Lady's Glove v.4*. Image courtesy of Laetitia Sonami. Photo credit: © F. Hoekzema.

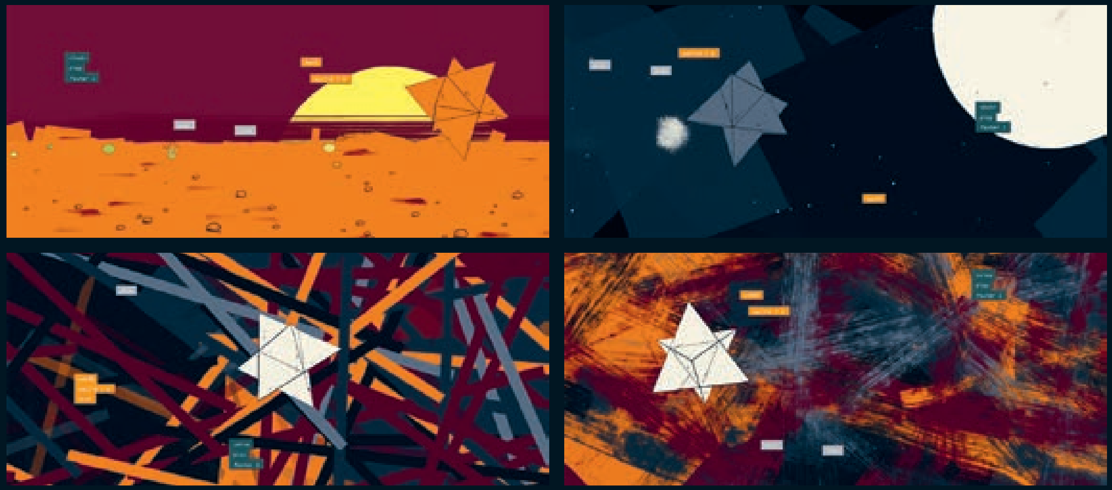
## 38 *On the Nature of L.A.R.S.*

## Michael Wollny and Martin Rohrmeier

*On the Nature of L.A.R.S.* ©Jörg Steinmetz.

## 39 *Life Codes*

## Alexandra Cárdenas



Top: *Life Codes* by A. Cardenas. Photo: ©Katya Goliath. Bottom: Life Codes. ©Roger Pibernat.

# *Apollo e Marsia*

## Jonathan Impett

Video of the viola d'amore, reminiscent of Apollo (left) and of the alto flute, reminiscent of Marsia (right). ©Shivadas De Schrijver.

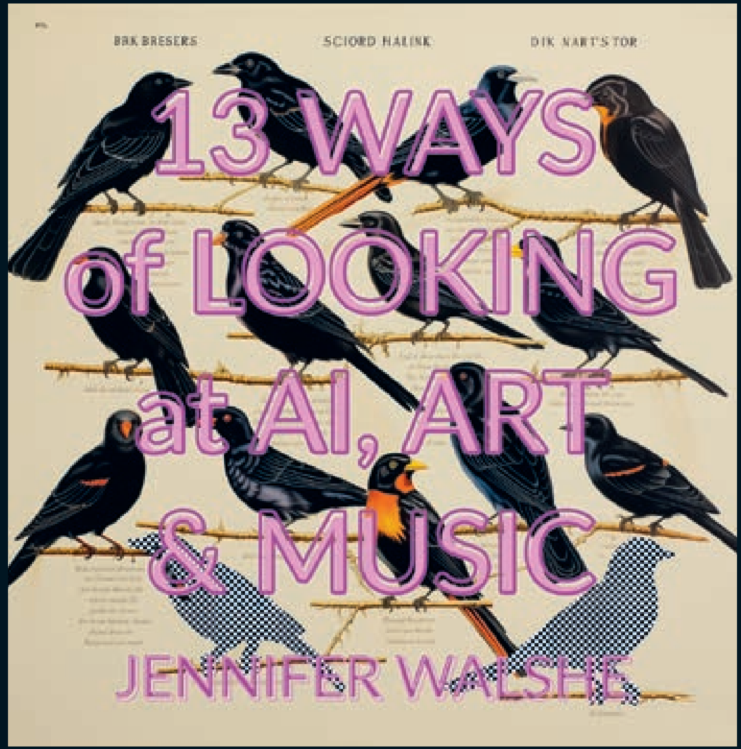
*The Contest Between Apollo and Marsia*, painted by Jacopo Tintoretto, 1545.



# *13 Ways of Looking at AI, Art & Music*

## Jennifer Walshe

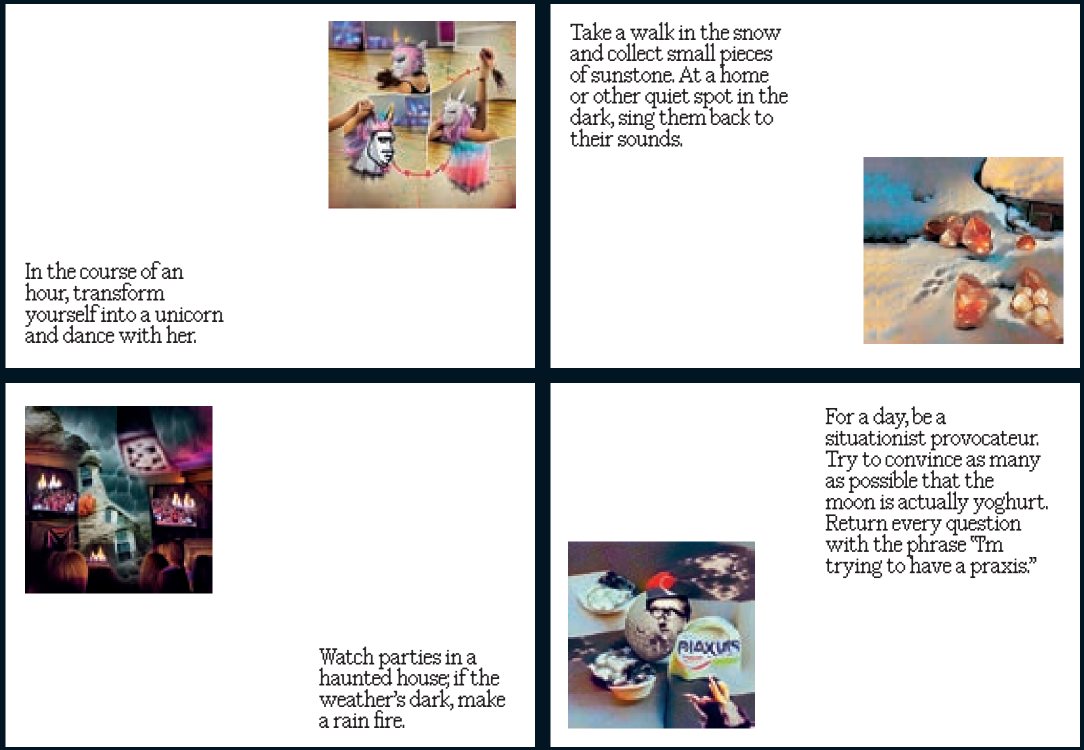

*AI is AI*. ©Jennifer Walshe.




*13 Ways of Looking at AI, Art & Music*, by Jennifer Walshe. ©Jennifer Walshe.

## 41.1 A / B *The Text Score Dataset 1.0*

## Jennifer Walshe




*The Text Score Dataset 1.0*. ©Jennifer Walshe.

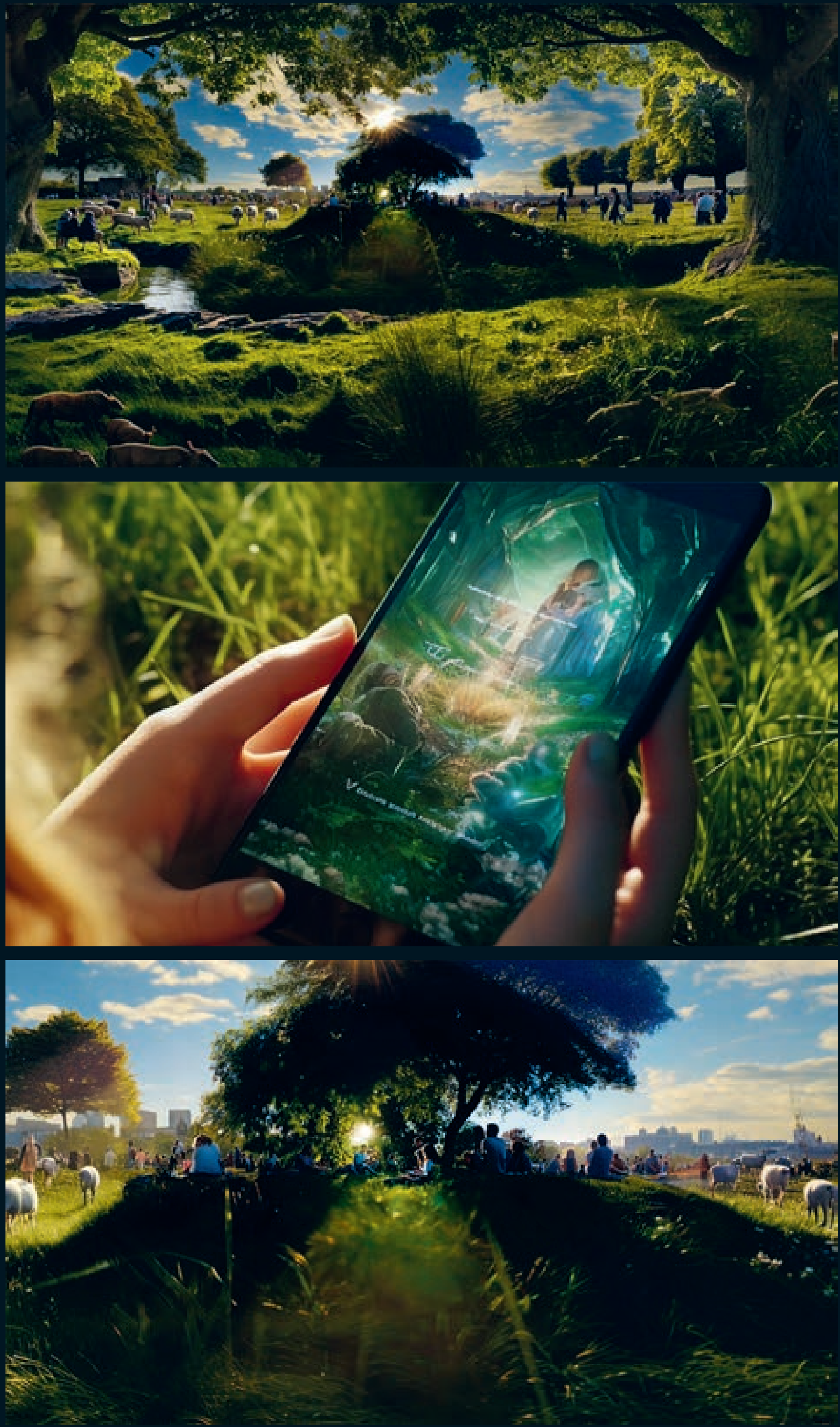
## 45.2 QUANTA

## Tomomi Adachi & Jennifer Walshe


QUANTA, performance by Tomomi Adachi and Jennifer Walshe. © Tomomi Adachi et Jennifer Walshe.

## 41.3 OSCAILT

## Jennifer Walshe



OSCAILT. ©Jennifer Walshe

## 41.4 ULTRACHUNK

### Memo Akten & Jennifer Walshe

Jennifer Walshe perfoming ULTRACHUNK. Photo credit © Anne Tetzlaff.

## 41.5 URSONATE%24

### Jennifer Walshe


Jennifer Walshe performing *Ursonate* in Darmstadt, Germany. ©Stefan Daub.

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EPFL Pavilions Lausanne

20.9.24–29.6.25

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Supposing [...] the fundamental relations of pitched sounds in the science of harmony and of musical composition were susceptible of such expression and adaptations, the engine might compose elaborate and scientific pieces of music of any degree of complexity or extent.

Ada Lovelace, in Richard Taylor, *Scientific Memoirs*, Vol. III, 1843

The sub-structure of music is much closer to the sub-structure of space and time. Music is purer, much closer to the categories of the mind.

Iannis Xenakis, *Formalized Music*, 1992


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