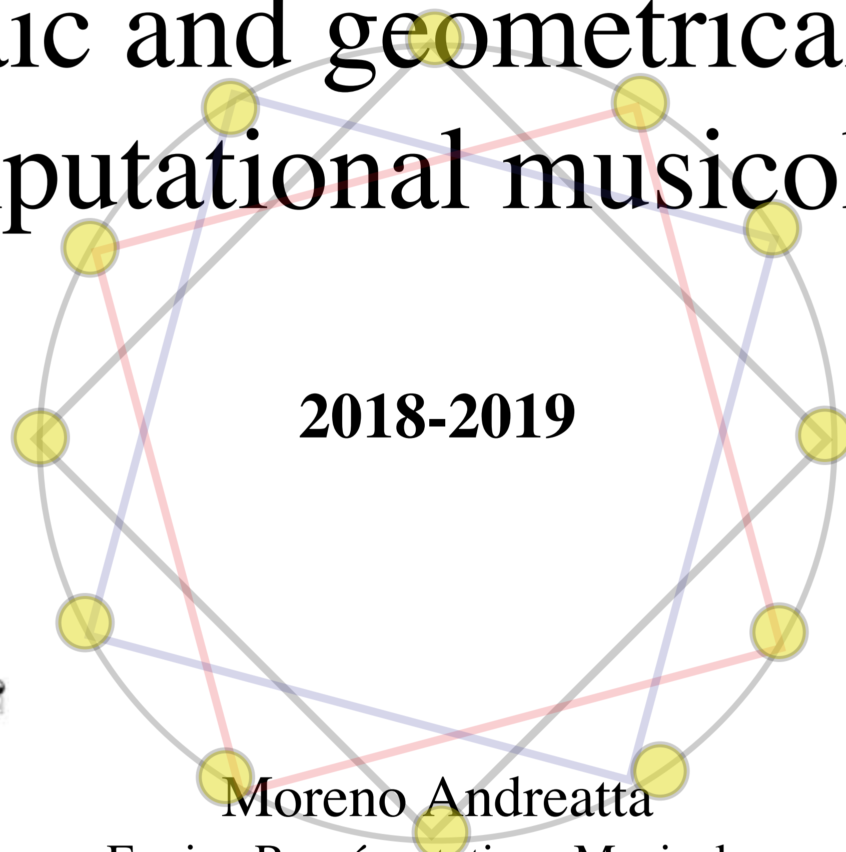
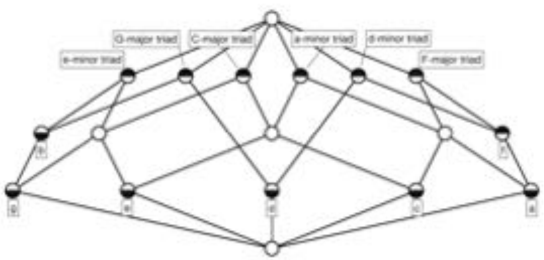
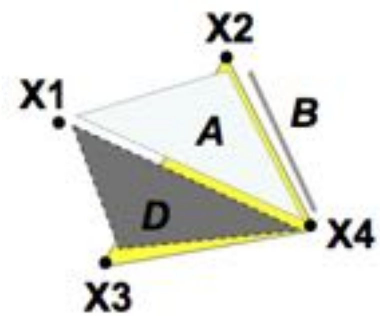
PARCOURS DU MASTER SCIENCES ET TECHNOLOGIES
UPMC • IRCAM • TELECOM PARISTECH

Algebraic and geometrical models in computational musicology (I)



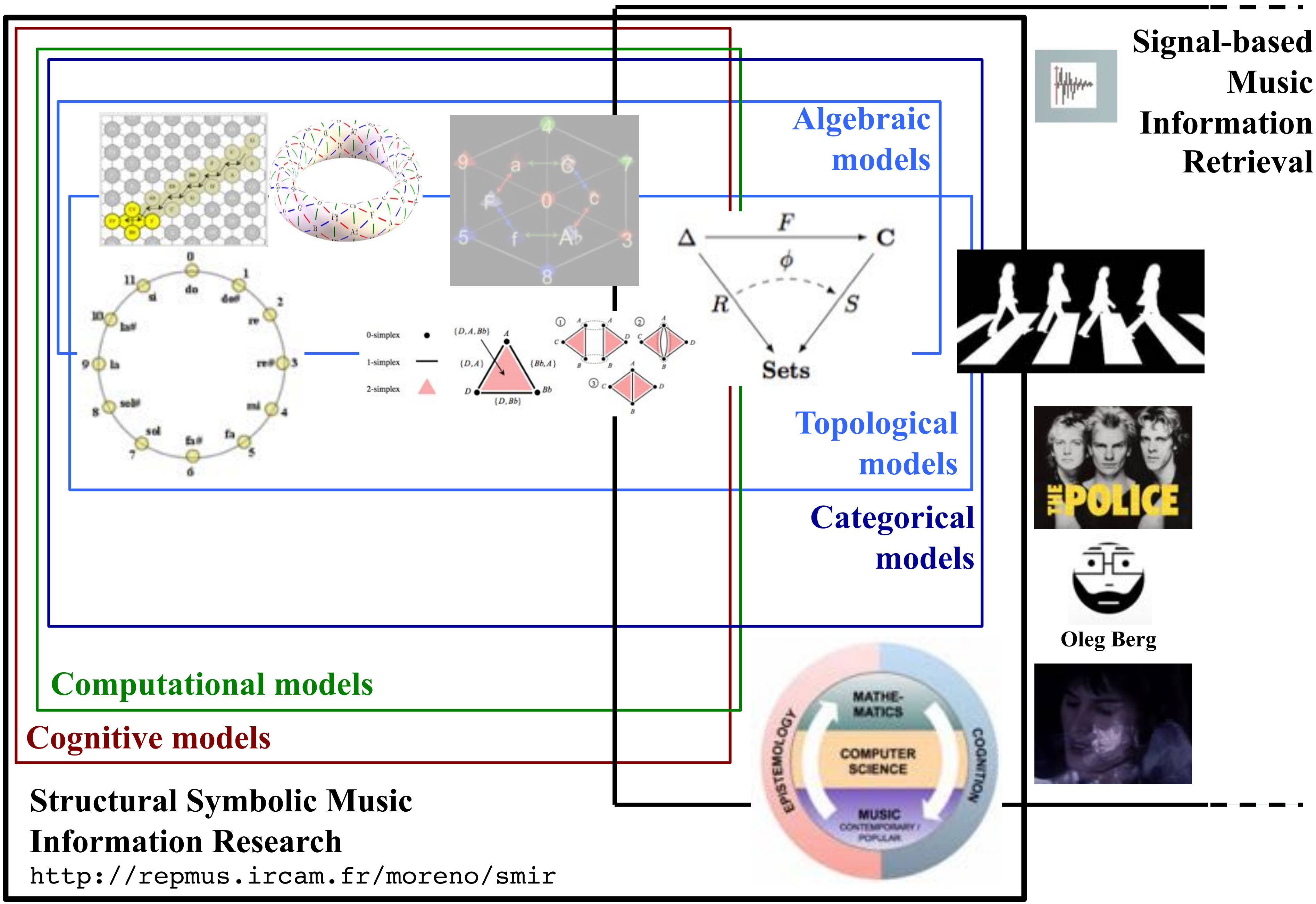
2018-2019





Moreno Andreatta
Equipe Représentations Musicales
IRCAM/CNRS/UPMC
http://www.ircam.fr/repmus.html

The SMIR Project: Structural Music Information Research



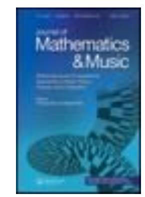
Computational Musicology in academic research

Conferences of the SMCM:

- 2007 Technische Universität (Berlin, Allemagne)
- 2009 Yale University (New Haven, USA)
- 2011 IRCAM (Paris, France)
- 2013 McGill University (Canada)
- 2015 Queen Mary University (Londres)
- 2017 UNAM (Mexico City)
- 2019 Universidad Complutense de Madrid (Spain)

Official Journal and MC code (00A65: Mathematics and Music)

- *Journal of Mathematics and Music*, Taylor & Francis
  (Editors: Th. Fiore, C. Callender | Associate eds.: E. Amiot, J. Yust)



Books Series:

- *Computational Music Sciences* Series, Springer (G. Mazzola & M. Andreatta eds. – 12 books published (since 2009)
- Collection *Musique/Sciences*, Ircam-Delatour France (J.-M. Bardez & M. Andreatta dir. – 16 books published (since 2006)

Some examples of PhD on maths & music

- **Alessandro Ratoci**, Vers l'hybridation stylistique assistée par ordinateur, PhD in music **composition & research**, Sorbonne University / IRCAM (cosupervised with Laurent Cugny)
- **Sonia Cannas**, *Représentations géométriques et formalisations algébriques en musicologie computationnelle*, PhD in **maths** in cotutelle agreement, **University of Pavia** (L. Pernazza) / **Université de Strasbourg** (A. Papadopoulos & M. Andreatta), 2018.
- **Grégoire Genuys**, *Théorie de l'homométrie et musique*, PhD in **maths**, **Sorbonne University** / IRCAM (cosupervised with Jean-Paul Allouche), 2017.
- **Hélianthe Caure**, *Pavages en musique et conjectures ouvertes en mathématiques*, PhD in **computer science**, **Sorbonne University** (cosupervised with Jean-Paul Allouche), 2016.
- **Mattia Bergomi**, *Dynamical and topological tools for (modern) music analysis,* PhD in **maths** in a cotutelle agreement Sorbonne University / University of Milan (cosupervised with Goffredo Haus, 2015).
- **Charles De Paiva**, *Systèmes complexes et informatique musicale*, thèse de doctorat, Programme Doctoral International « Modélisation des Systèmes Complexes », PhD in **musicology** in a cotutelle agreement, **Sorbonne University** / **UNICAMP**, Brésil, 2016.
- **John Mandereau**, *Des systèmes d'Intervalles Généralisés aux Systèmes Evolutifs à Mémoire : aspects théoriques et computationnels*, thèse de doctorat en mathématiques, PhD in cotutelle agreement **University of Pisa** / **Sorbonne University** (cosupervised with F. Acquistapace). PhD in **maths** (aborted).
- **Louis Bigo**, *Représentation symboliques musicales et calcul spatial*, PhD in **computer science**, **University of Paris Est Créteil** / **IRCAM**, 2013 (cosupervised with Olivier Michel and Antoine Spicher)
- **Emmanuel Amiot**, *Modèles algébriques et algorithmiques pour la formalisation mathématique de structures musicales*, PhD in, **Sorbonne University** / **IRCAM**, 2010 (cosupervised with Carlos Agon) **computer science**
- **Yun-Kang Ahn**, *L'analyse musicale computationnelle*, PhD in **computer science**, **Sorbonne University** / **IRCAM**, 2009 (cosupervised with Carlos Agon)

UNIVERSITÉ DE STRASBOURG

SORBONNE UNIVERSITÉ

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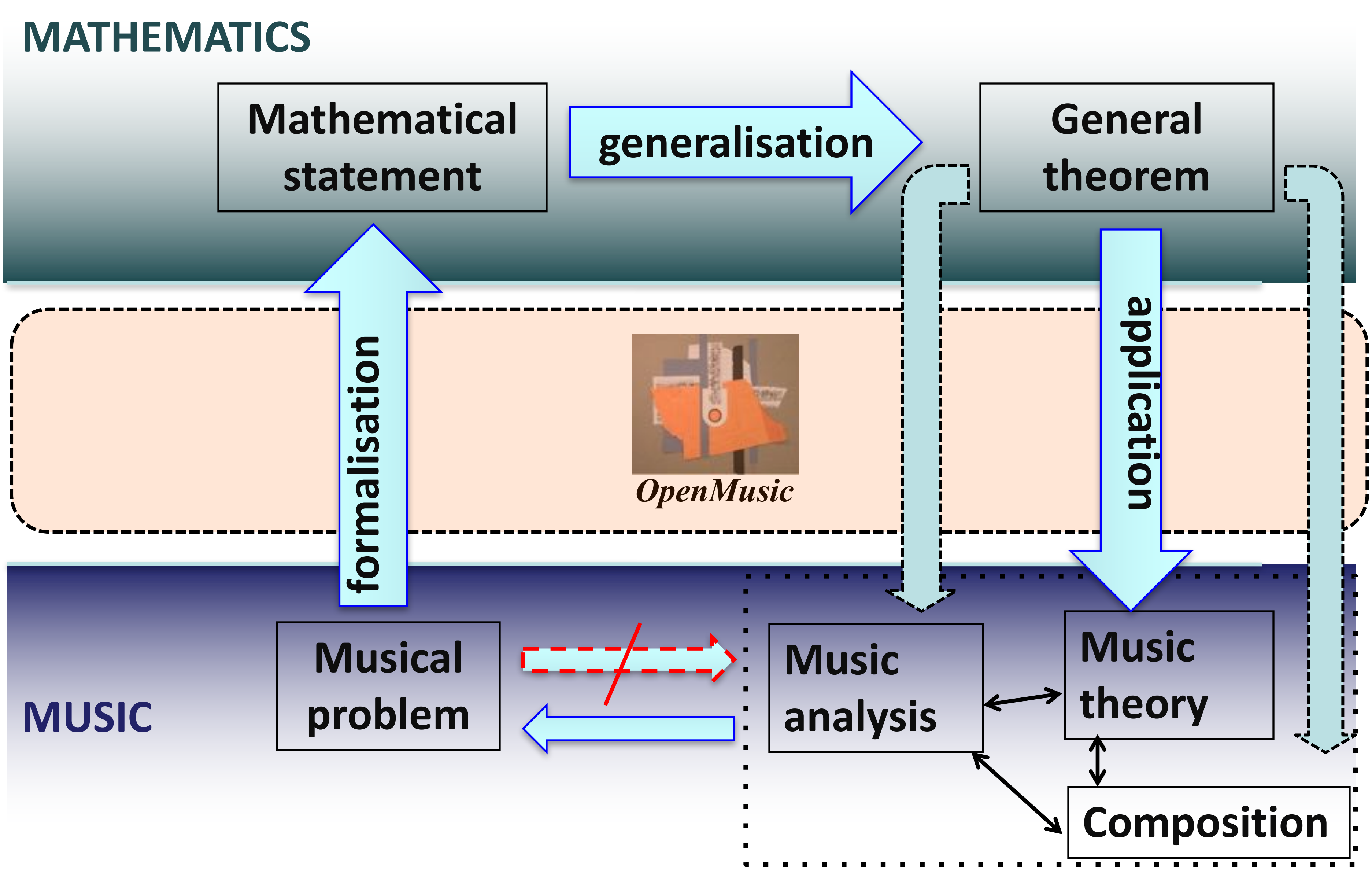
UPEC UNIVERSITÉ PARIS-EST CRÉTEIL VAL DE MARNE

ircam Centre Pompidou

The double movement of a ‘mathemusical’ activity

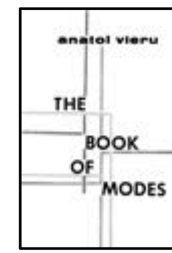


Periodic sequences and finite difference calculus

$$Df(x)=f(x)-f(x-1)$$

$$
\begin{array}{lcl}
f & = & 7\ 11\ 10\ 11\ 7\ 2\ \ 7\ 11\ 10\ 11\ 7\ 2\ \ 7\ 11\ldots \\
Df & = & 4\ 11\ 1\ 8\ 7\ 5\ \ 4\ 11\ 1\ 8\ 7\ 5\ \ 4\ 11\ldots \\
D^2 f & = & 7\ 2\ 7\ 11\ 10\ \ 11\ 7\ 2\ 7\ 11\ 10\ 11\ldots \\
D^3 f & = & 7\ 5\ 4\ 11\ 1\ 8\ \ 7\ 5\ 4\ 11\ 1\ 8\ldots \\
D^k f & = & \ldots\ldots
\end{array}
$$

Anatol Vieru



V	0	3	8	7	11	0	11	10	6	9	0	9	1	2	9	8	4	3	6
VIII	0	0	0	0	3	3	7	2	0	0	0	6	3	3	3	4	8	0	0
IV	3	3	4	4	1	11	11	8	3	3	9	4	1	7	11	8	11	3	9
IX	0	0	0	0	0	3	6	[1]	3	3	3	3	9	0	3	6	[10]	6	6
IV	0	10	3	9	10	0	9	7	0	6	7	9	6	4	9	3	4	6	3

Anatol Vieru: *Zone d'oubli* pour alto (1973)

Reducible and reproducible sequences

$$f = 11\ 6\ 7\ 2\ 3\ 10\ {\scriptstyle 11\ 6}\ \ldots$$
$$Df = 7\ 1\ 7\ 1\ 7\ 1\ 7\ 1\ldots$$
$$D^2f = 6\ 6\ 6\ 6\ 6\ldots$$
$$D^4f = 0\ 0\ 0$$

Reducible sequences:
$\exists\ k \geq 1$ such that
$D^k f = 0$

$$f = 7\ 11\ 10\ 11\ 7\ 2\ {\scriptstyle 7\ 11}\ \ldots$$
$$Df = 4\ 11\ 1\ 8\ 7\ 5\ {\scriptstyle 4\ 11\ 1}\ \ldots$$
$$D^2f = 7\ 2\ 7\ 11\ 10\ 11\ {\scriptstyle 7\ 2\ 7}\ \ldots$$
$$D^3f = 7\ 5\ 4\ 11\ 1\ 8\ {\scriptstyle 7\ 5\ 4\ 11\ 1\ 8}\ldots$$
$$D^4f = 10\ 11\ 7\ 2\ 7\ 11\ {\scriptstyle 10\ 11}\ \ldots$$
$$D^5f = 1\ 8\ 7\ 5\ 4\ 11\ {\scriptstyle 1\ 8}\ \ldots$$
$$D^6f = 7\ 11\ 10\ 11\ 7\ 2\ {\scriptstyle 7\ 11}\ \ldots$$

Reproducible sequences:
$\exists\ k \geq 1$ such that
$D^k f = f$

A decomposition property of any periodic sequence

$Df(x)=f(x)-f(x-1).$

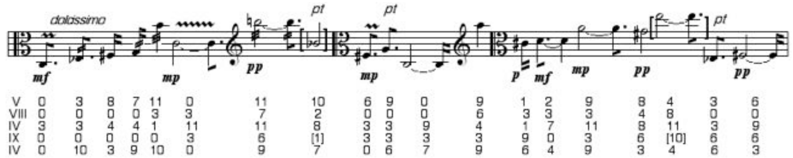
7 11 10 11 7 2 7 11 10 11 7 2 7 11…

4 11 1 8 7 5 4 11 1 8 7 5 4 11…

7 2 7 11 10 11 7 2 7 11 10 11…

7 5 4 11 1 8 7 5 4 11 1 8…

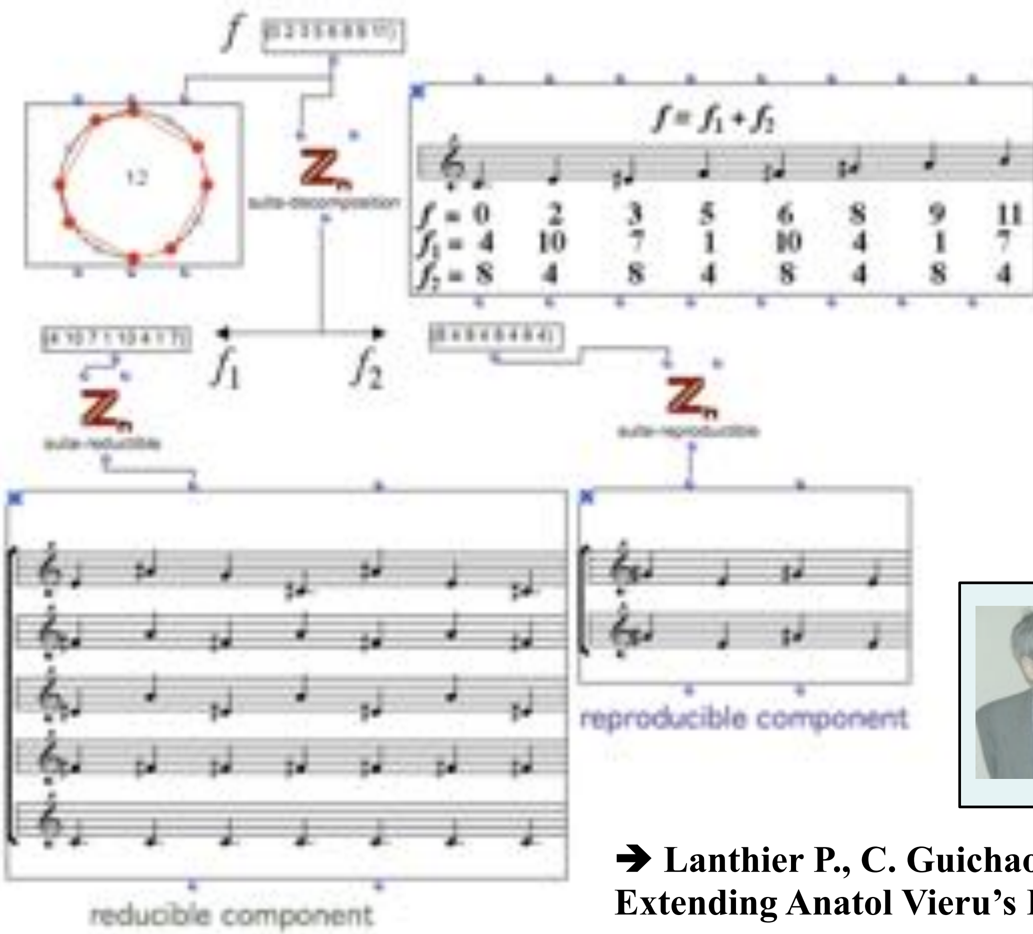
……



Anatol Vieru: *Zone d'oubli* for viola (1973)

Reducible sequences:
$\exists\, k\geq 1$ such that $D^k f = 0$

Reproducible sequences:
$\exists\, k\geq 1$ such that $D^k f = f$



- **Decomposition theorem**

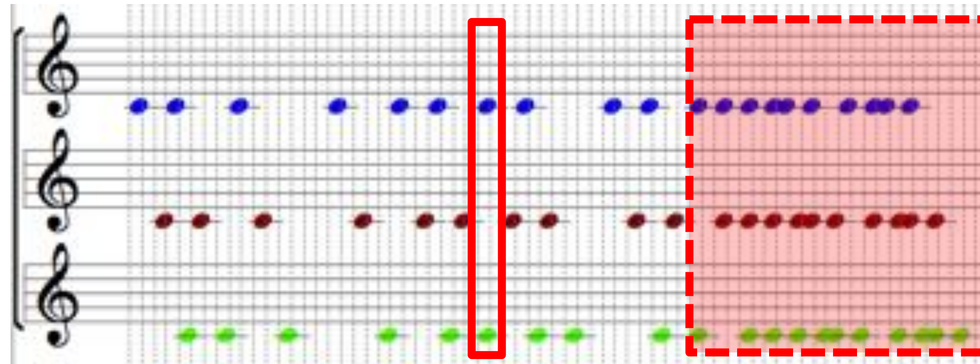
(Vuza & Andreatta, *Tatra M.*, 2001)
Every periodic sequence f can be decomposed in a unique way as a sum $f_1 + f_2$ of a reducible sequence f_1 and a reproducible sequence f_2

D. Vuza, M. Andreatta (2001), « On some properties of periodic sequences in Anatol Vieru's modal theory », Tatra Mountains Mathematical Publications, Vol. 23, p. 1-15

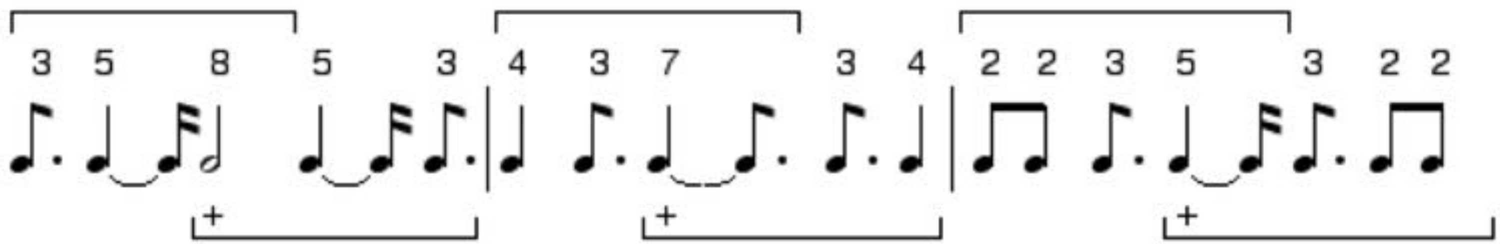
➔ Lanthier P., C. Guichaoua, M. Andreatta (2019), "Reinterpreting and Extending Anatol Vieru's Periodic Sequences Through the Cellular Automata Formalisms", in M. Montiel et al. (eds), *Proc. MCM 2019*, Springer.

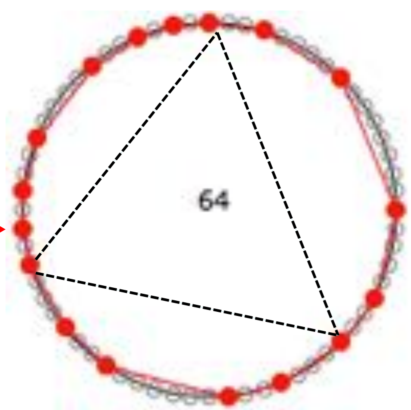
Periodic rhythmic sequences and tiling canons

Harawi (1945)



***Harawi*: rhythmic reduction**



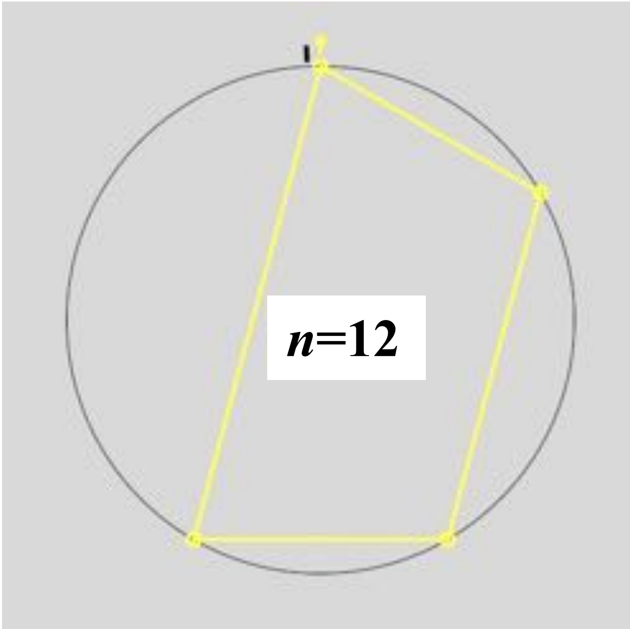


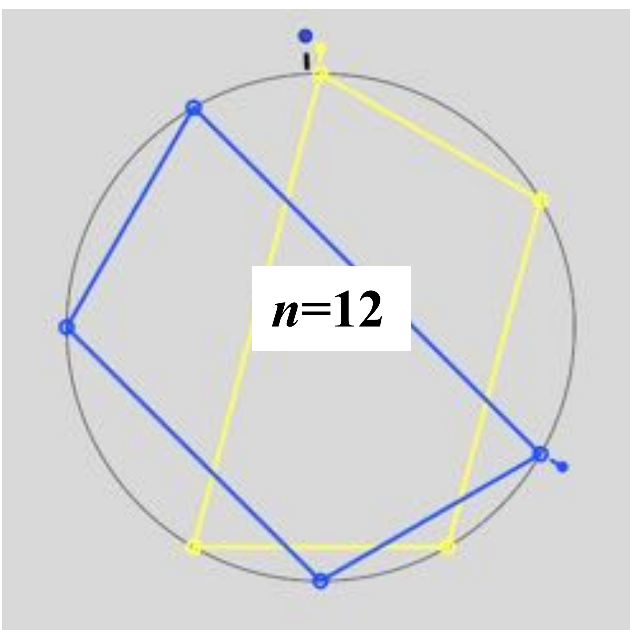
« …il résulte de tout cela que les différentes sonorités se mélangent ou s’opposent de manières très diverses, jamais au même moment ni au même endroit […]. C’est du désordre organisé »

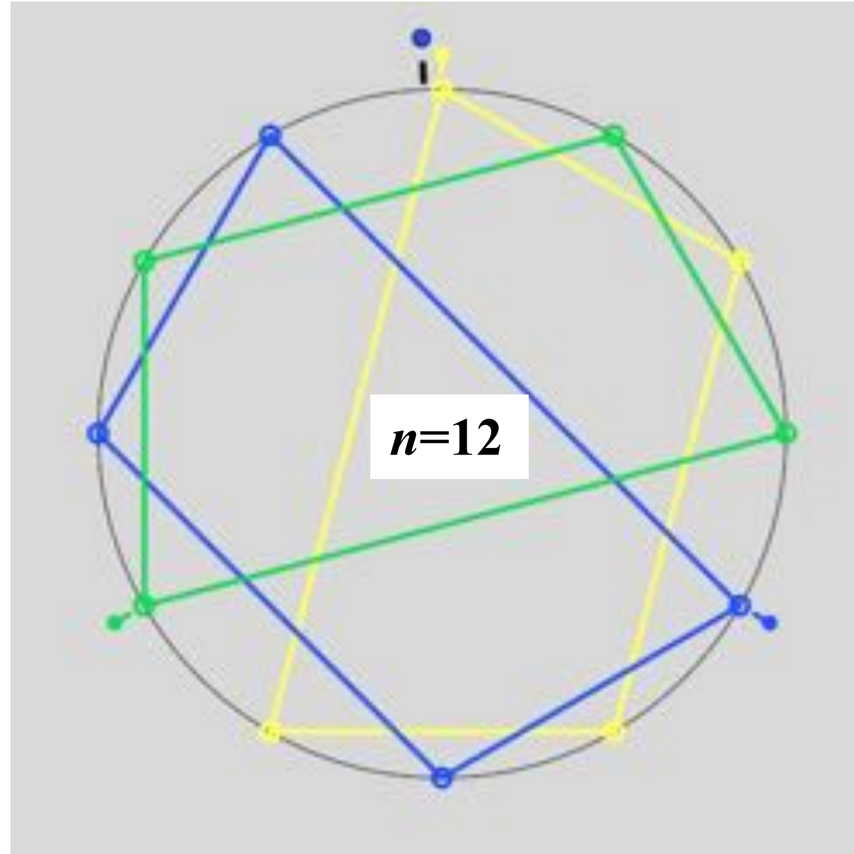
O. Messiaen: *Traité de Rythme, de Couleur et d’Ornithologie,* tome 2, Alphonse Leduc, 1992.

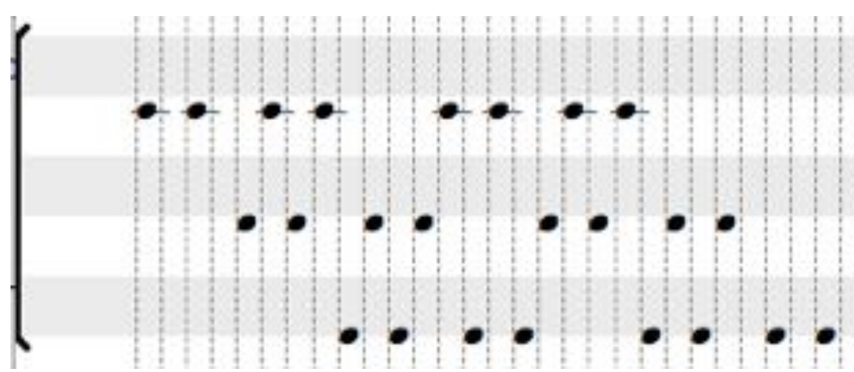
Olivier Messiaen

Tiling the time axis with translates of one tile

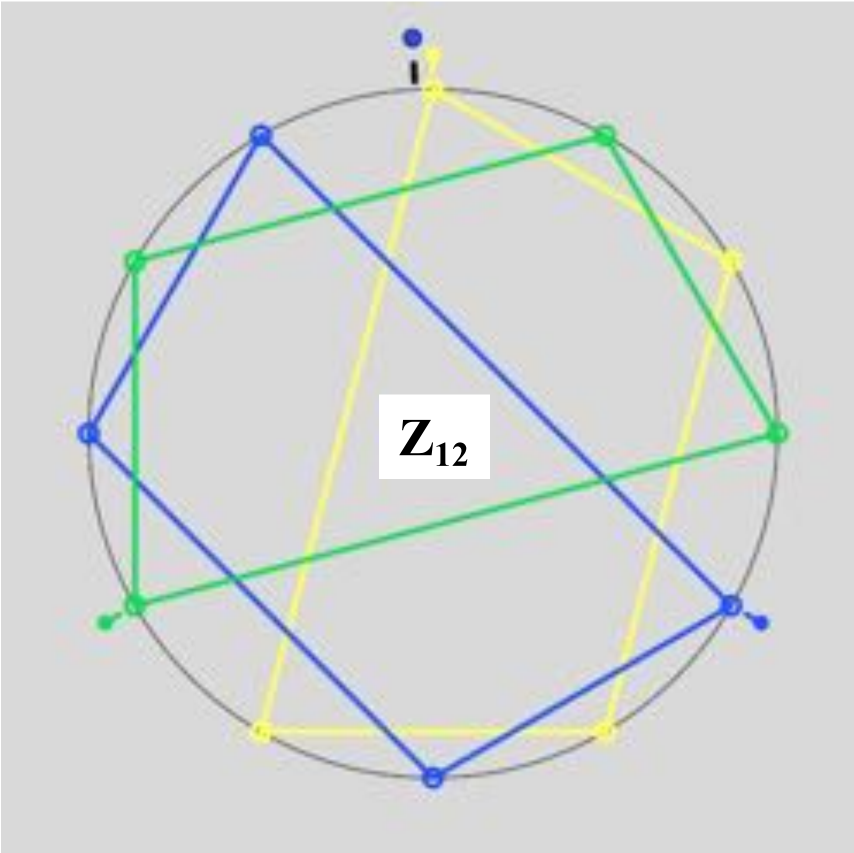


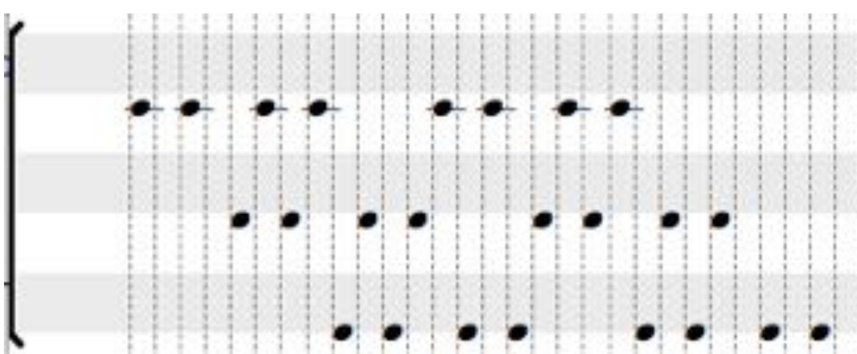






Formalizing the tiling process as a direct sum of subsets





$A_1 = \{0, 2, 5, 7\}$

$\downarrow T_4$

$A_2 = \{4, 6, 9, 11\}$

$\downarrow T_4$

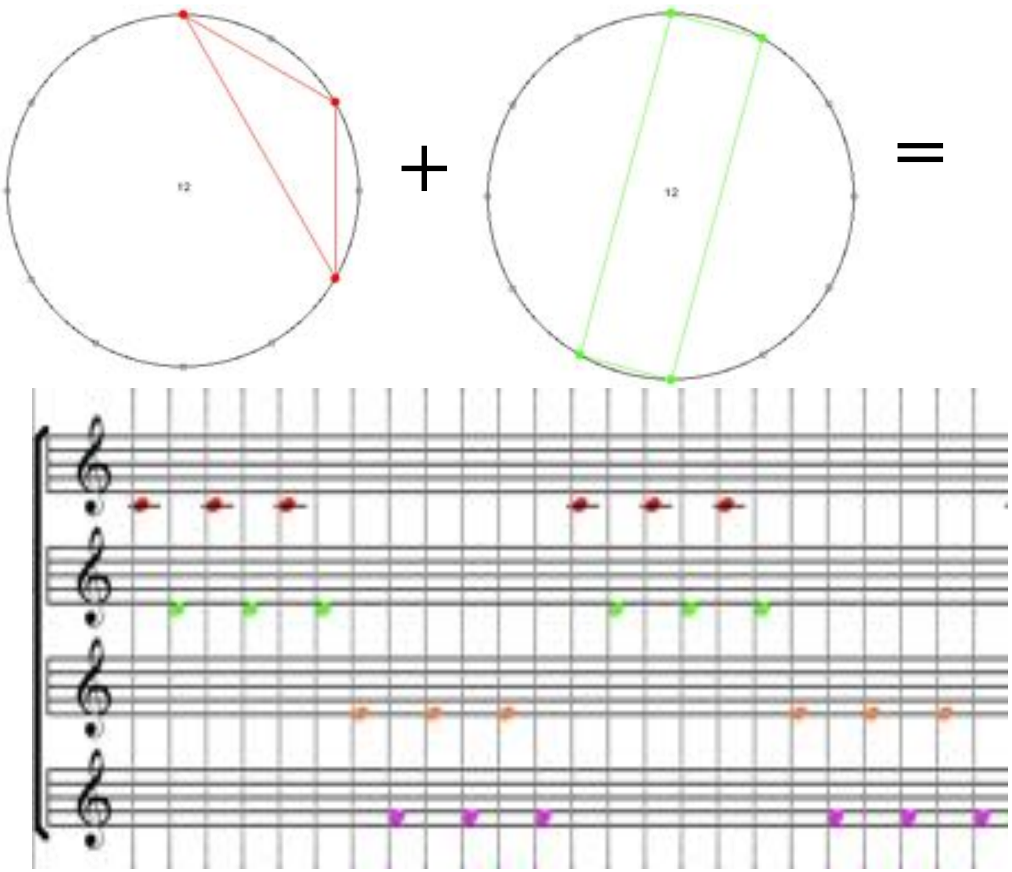
$A_3 = \{8, 10, 1, 3\}$

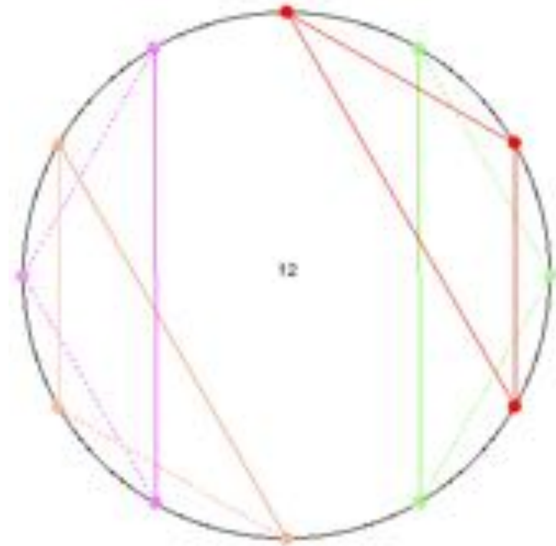
$Z_{12} = A_1 \cup A_2 \cup A_3$

$Z_{12} = A \oplus B$

$A = \{0,2,5,7\}$
$B = \{0,4,8\}$

Rhythmic tiling canons with no regular entries



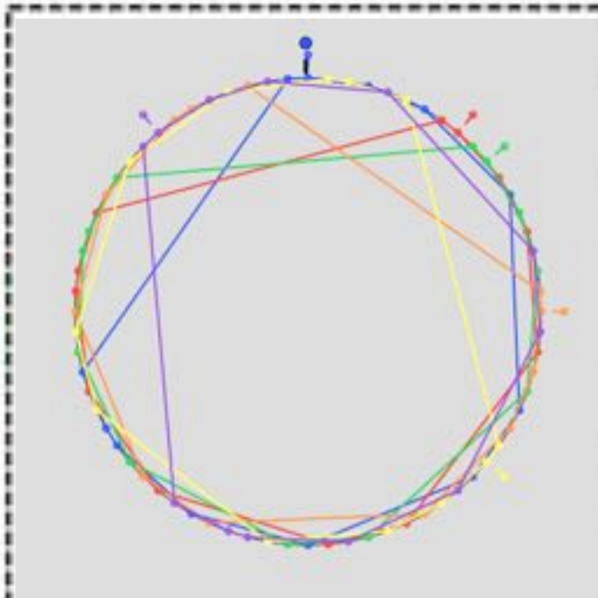


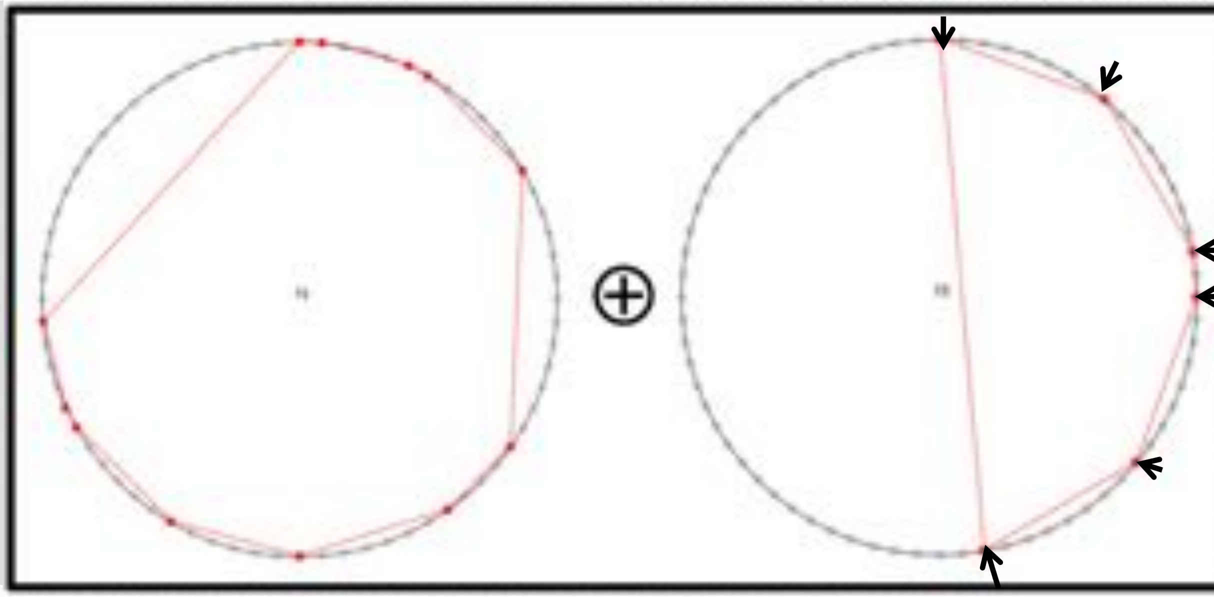
transpositional combination

$$\{0,2,4\}\oplus\{0,1,6,7\} = \mathbb{Z}_{12} = (2\ 2\ 8)\bullet(1\ 5\ 1\ 5)$$

One of the two factors is a Messiaen's mode of limited transposition

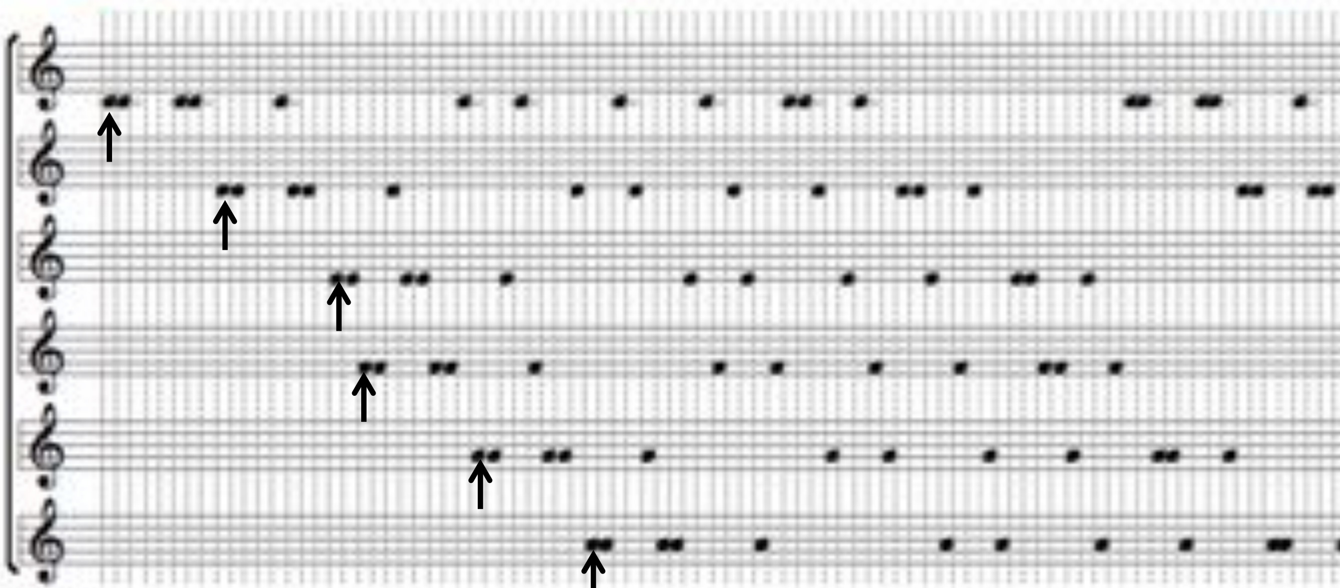
Aperiodic Rhythmic Tiling Canons (Vuza Canons)



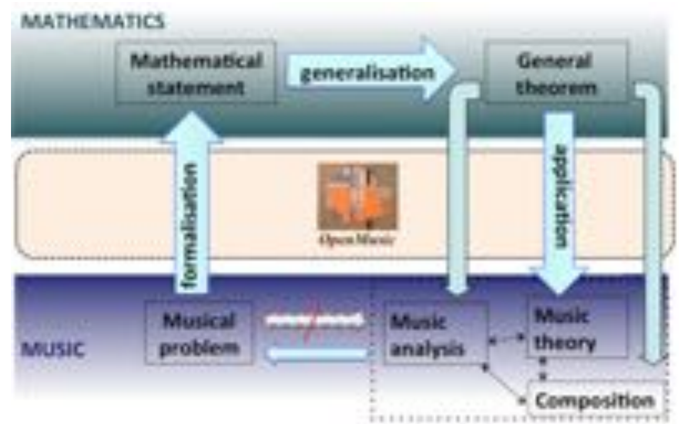


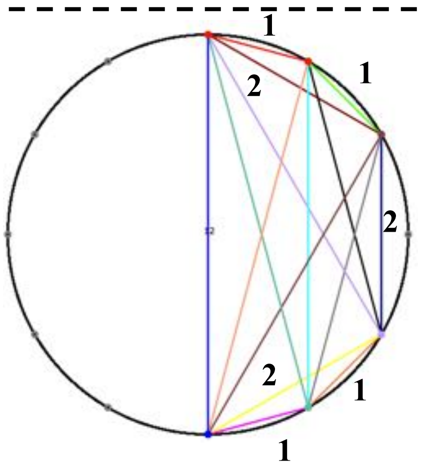
Dan Vuza

Anatol Vieru



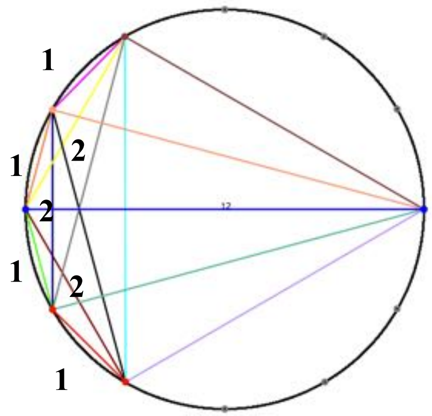
A historical example of "mathemusical" problem

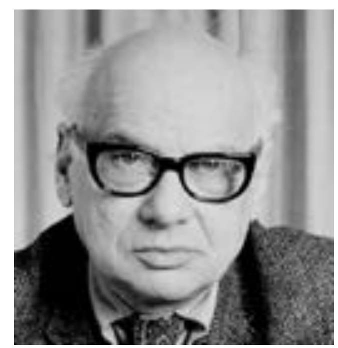




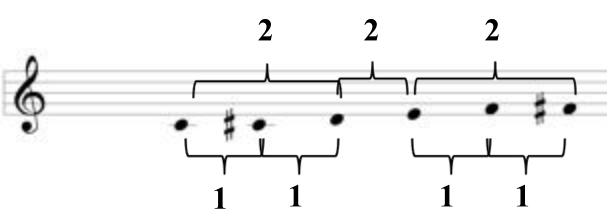
HOMOMETRY

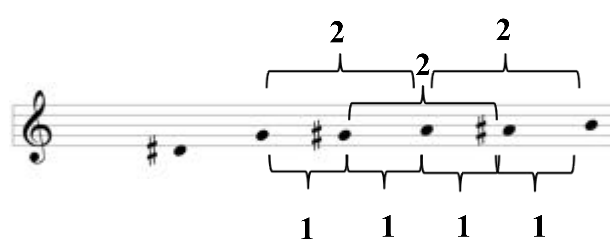
Hexachord Theorem



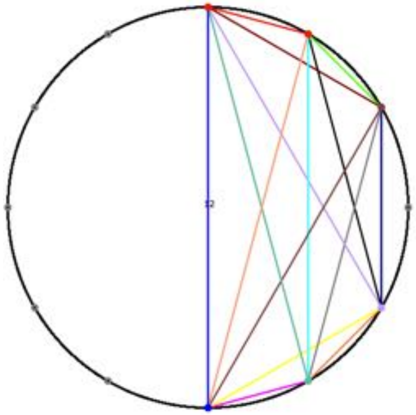


M. Babbitt





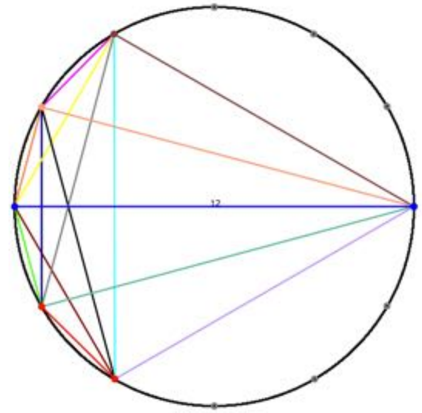
The shortest proof of Babbitt's Theorem?



$\approx$

$\longleftrightarrow$

Hexachord Theorem



M. Babbitt

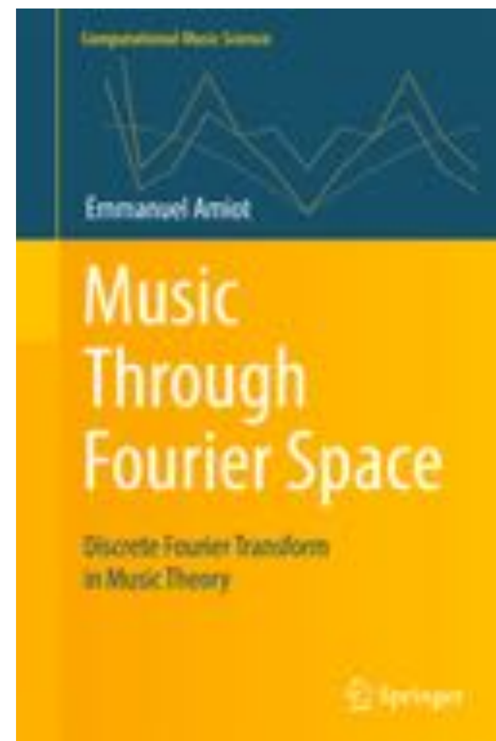
$IC_A = [4, 3, 2, 3, 2, 1\,] = [4, 3, 2, 3, 2, 1\,] = IC_{A'}$

$$IC_A(k) = (1_A \star 1_{-A})(k)$$

$$\mathcal{F}_A : t \mapsto \sum_{k \in A} e^{-2i\pi kt/c}$$

$$\forall \mathrm{k}\ \mathcal{F}(\mathrm{IC}_{\mathbb{Z}_c \setminus A})(\mathrm{k}) = \mathcal{F}(\mathrm{IC}_A)(\mathrm{k})$$

E. Amiot : « Une preuve élégante du théorème de Babbitt par transformée de Fourier discrète », Quadrature, 61, 2006.



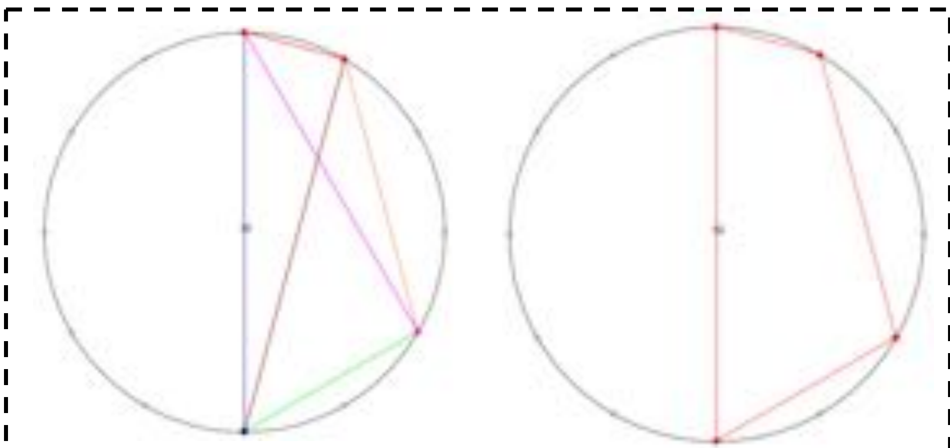
Z-relation, homometry and phase retrieval problem

- Two sets are Z-related if they have the same module of the DFT

$$IC_A(k) = (1_A \star 1_{-A})(k)$$

$$\mathcal{F}_A : t \mapsto \sum_{k \in A} e^{-2i\pi kt/c}$$

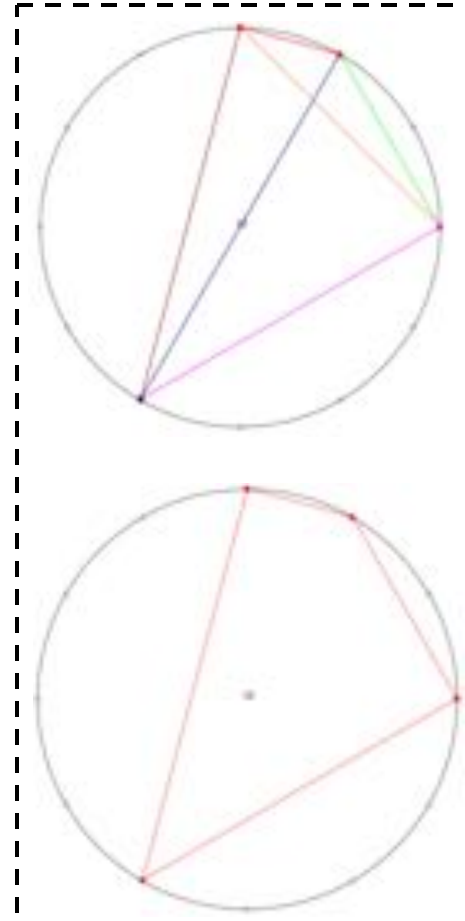
$$\mathcal{F}(IC_A) = \mathcal{F}_A \times \mathcal{F}_{-A} = |\mathcal{F}_A|^2$$



Z-relation

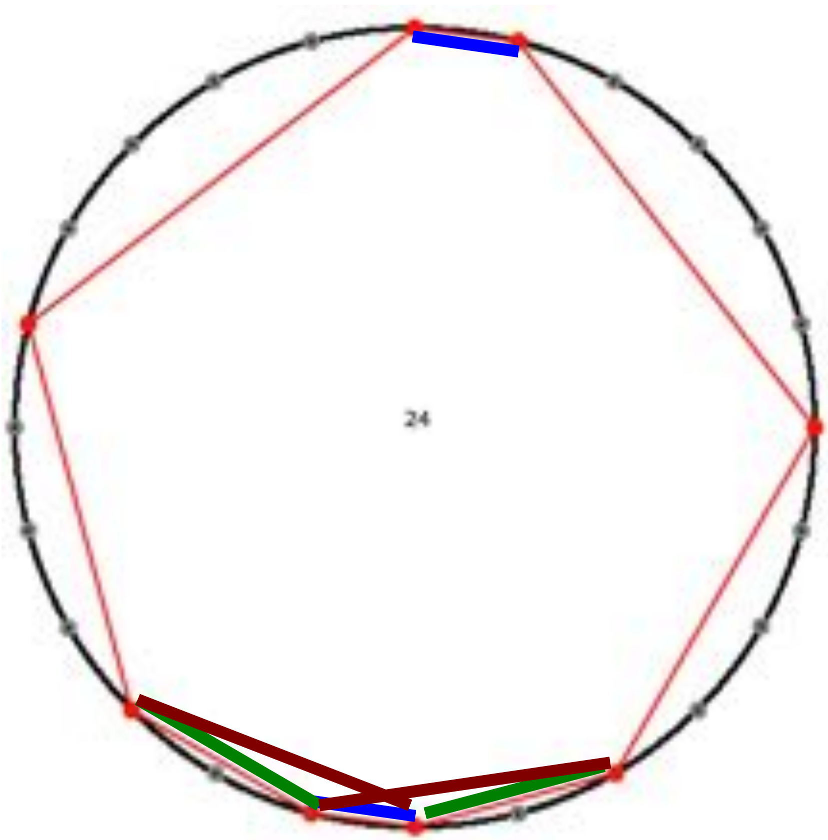
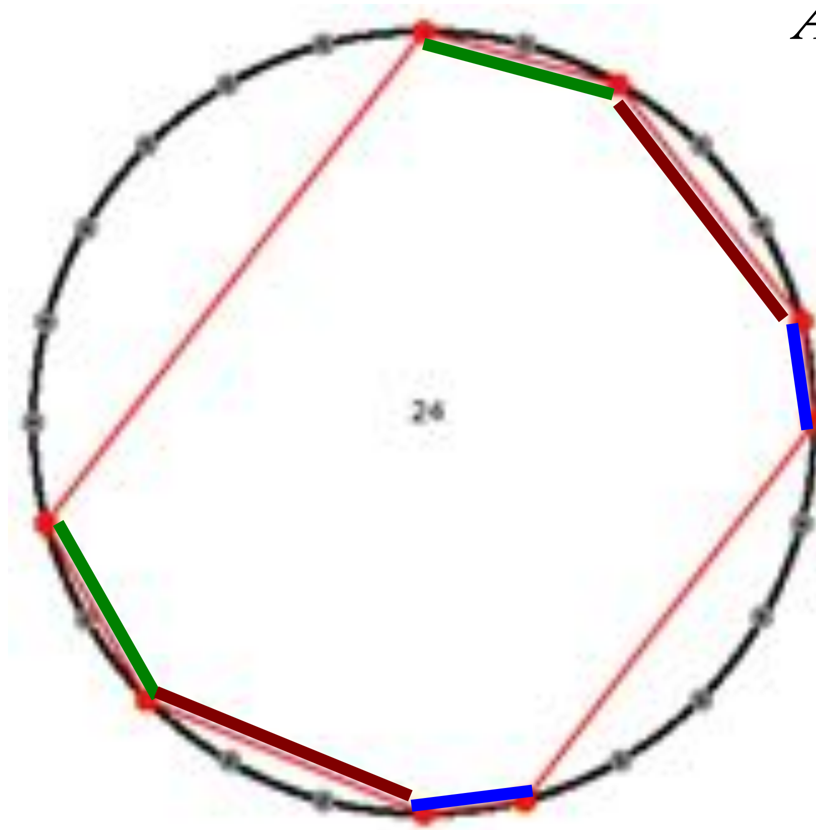
$\longleftrightarrow$

homometry



- **Mandereau J., D. Ghisi, E. Amiot, M. Andreatta, C. Agon, (2011), « Z-relation and homometry in musical distributions »,** ***Journal of Mathematics and Music*****, vol. 5, n° 2, p. 83-98.**
- **Mandereau J, D. Ghisi, E. Amiot, M. Andreatta, C. Agon (2011), « Discrete phase retrieval in musical structures »,** ***Journal of Mathematics and Music*****, vol. 5, n° 2, p. 99-116.**

Z-relation (music) and homometry (cristallography)

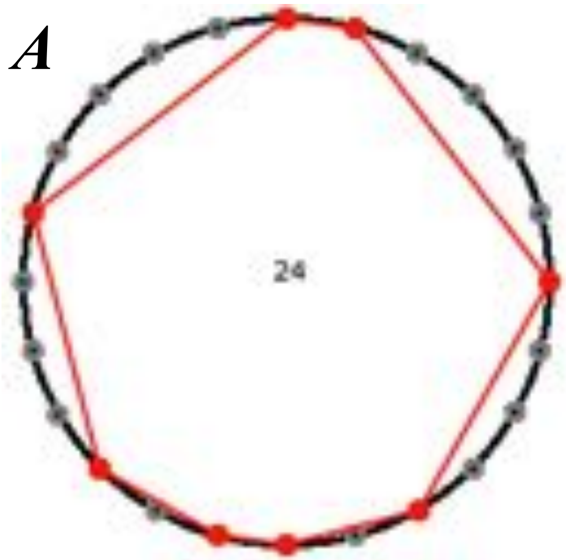
A   A'

$$IC_A(k) = (1_A \star 1_{-A})(k)$$

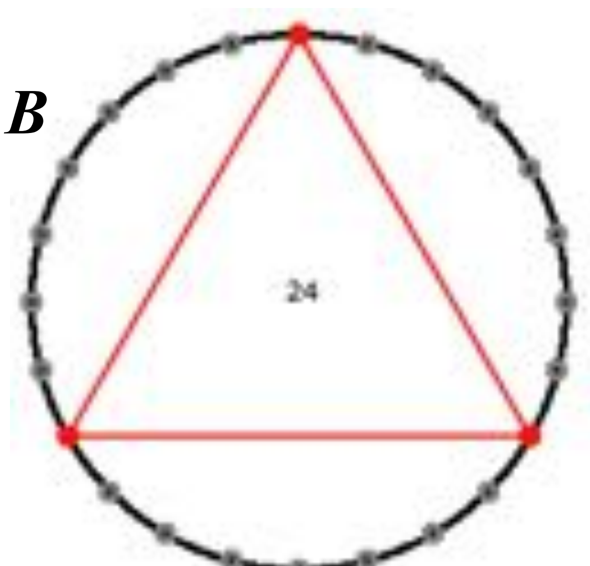
$$A \sim A' \quad \overset{Z\text{-relation}}{\underset{Homometry}{\Longleftrightarrow}} \quad IC_A(k) = IC_{A'}(k) \quad \Longleftrightarrow \quad |F_A|^2 = |F_{A'}|^2$$

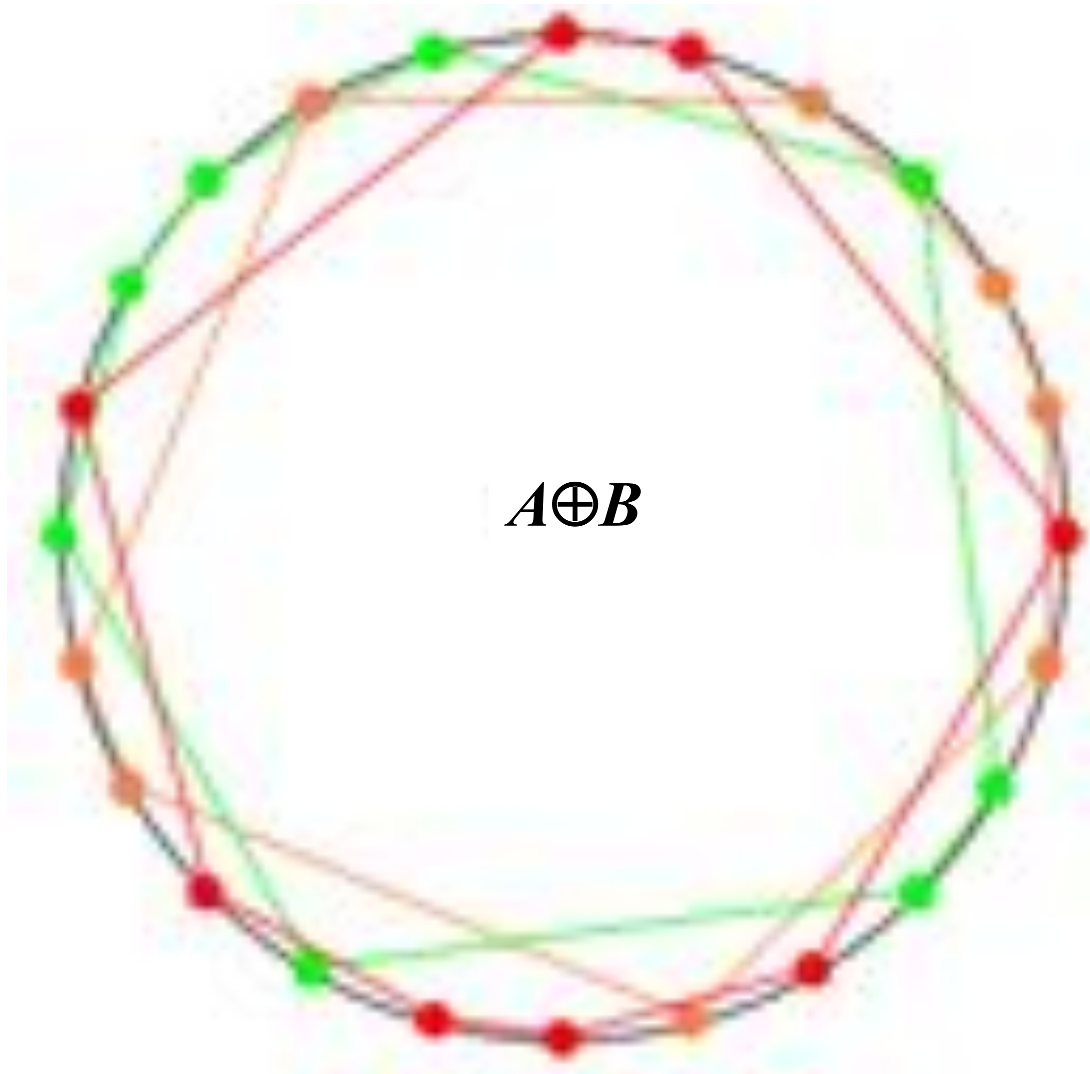
Tiling Rhythmic Canons and Homometry

A



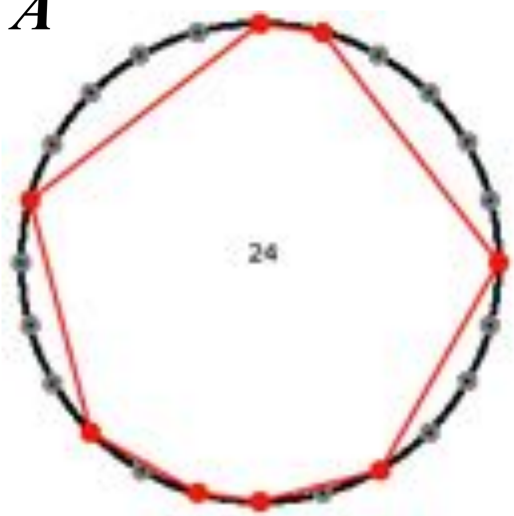
B



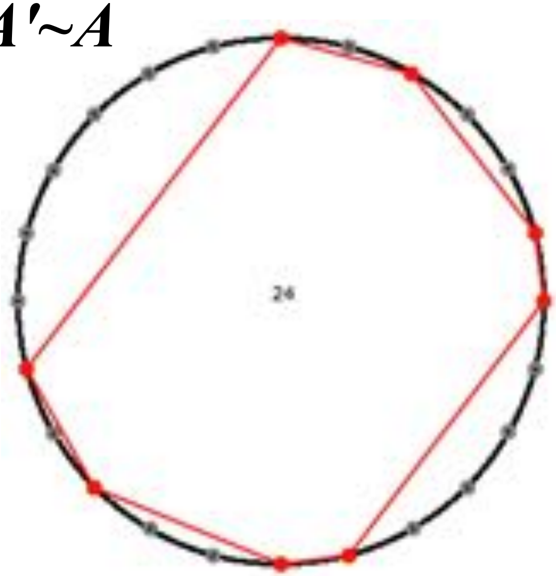


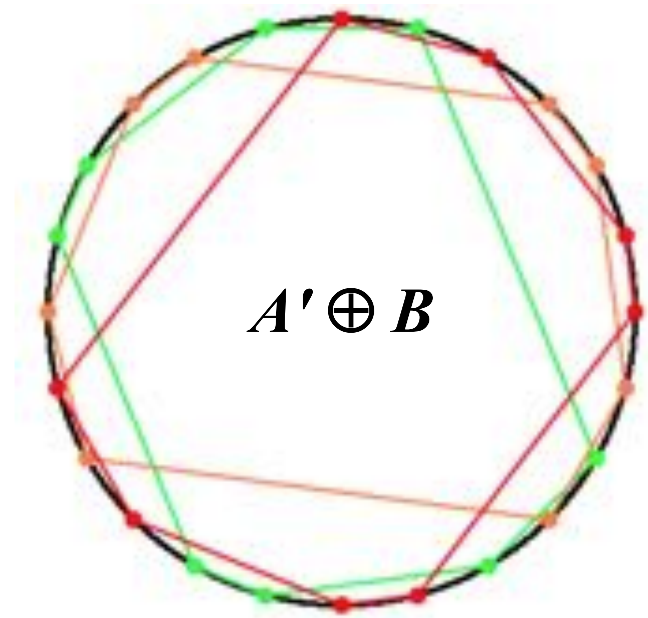
Tiling Rhythmic Canons and Homometry

A

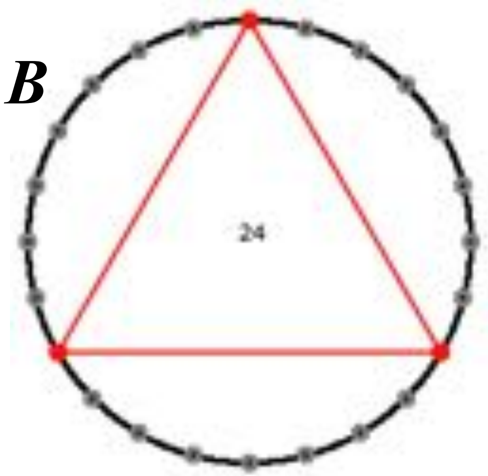


A′~A





B

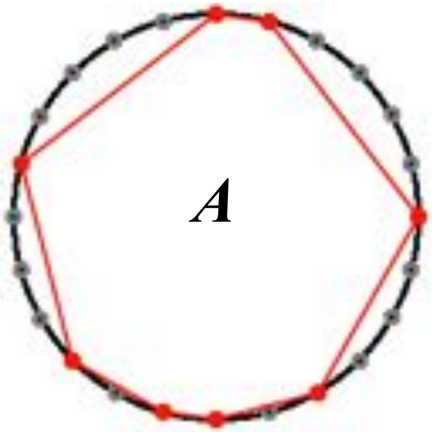


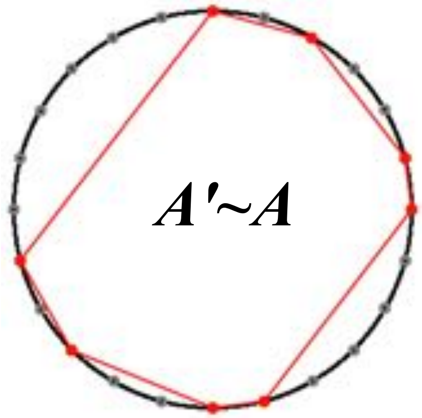
***A musical offering*:**

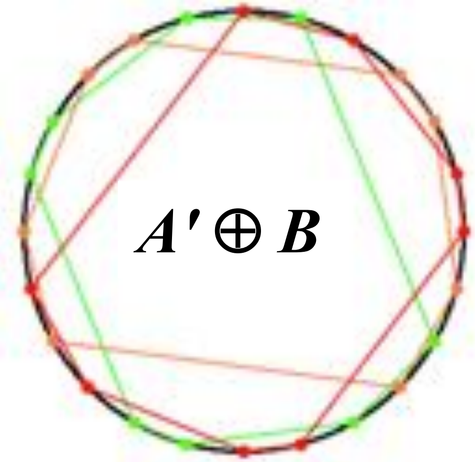
- ***Theorem*:**
  If A tiles with B and A' has the same IC, then A' tiles with B, too.

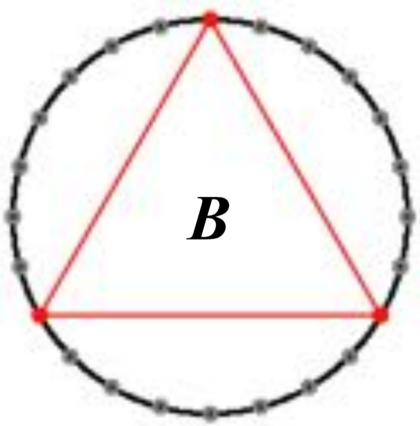
E. Amiot, « New Perspectives on Rhythmic Canons and the Spectral Conjecture », *JMM*, 2009.

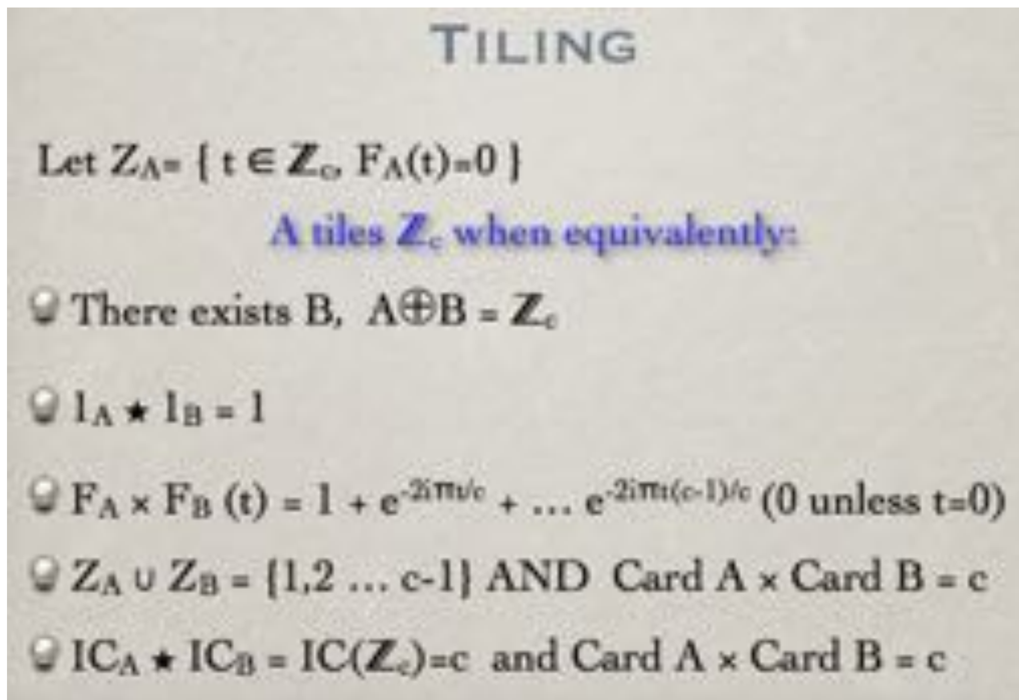
Tiling Rhythmic Canons and Homometry





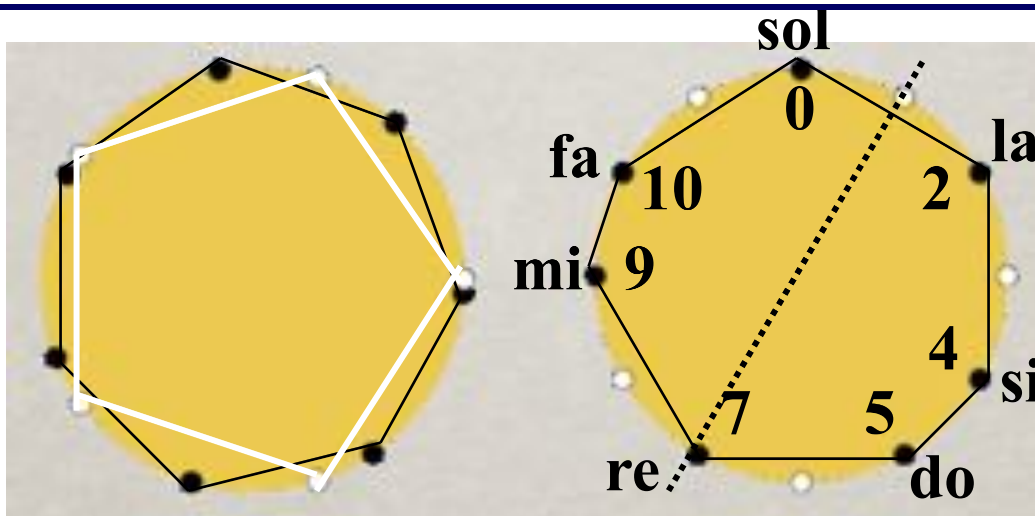






E. Amiot, « New Perspectives on Rhythmic Canons and the Spectral Conjecture », *JMM*, 2009.

Maximally Even Sets



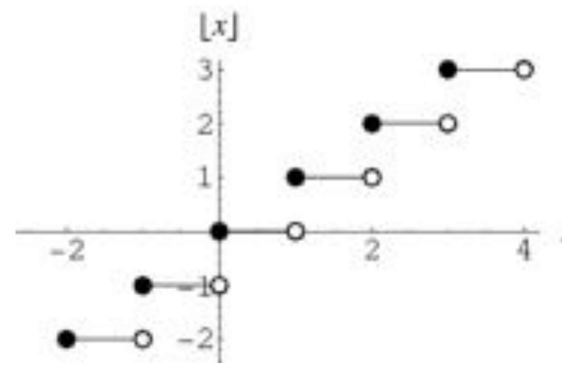
Diatonic scale:
{0, 2, 4, 5, 7, 9, 10}

Pentatonic scale:
{1, 3, 6, 8, 11}

Definition (Clough-Myerson-Douthett) A set A with cardinality d in a given equal tempered space $\mathbf{Z}_c$ is maximally even if $A = \{a_k\}$

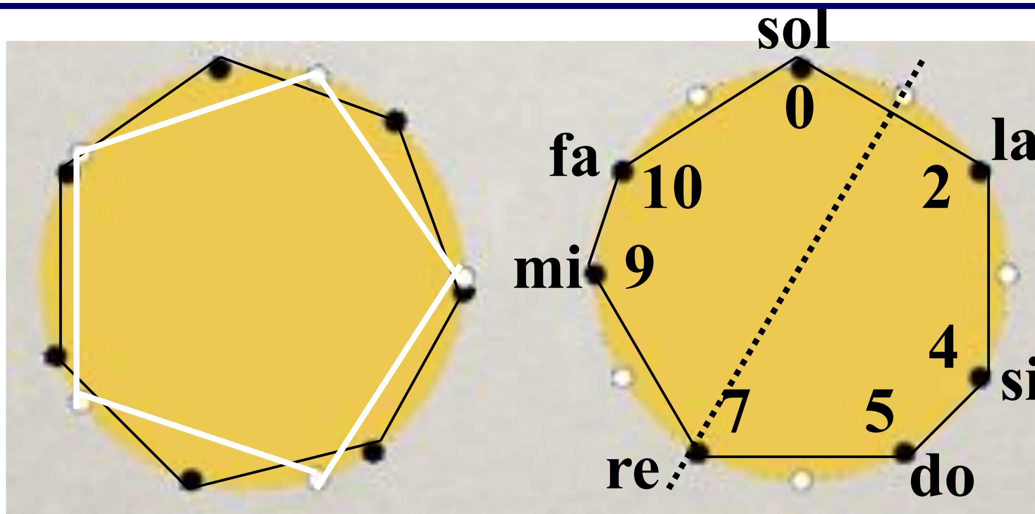
$$a_k = J^{\alpha}_{c,d}(k) = \lfloor \frac{kc+\alpha}{d} \rfloor$$

where $\alpha \in \mathbf{R}$
$\lfloor x \rfloor$ is the integer part of x



$$J^5_{12,7} = \left\{ \left\lfloor \frac{12k+5}{7} \right\rfloor \right\}_{k=0}^{6} = \{0,2,4,5,7,9,11\}$$

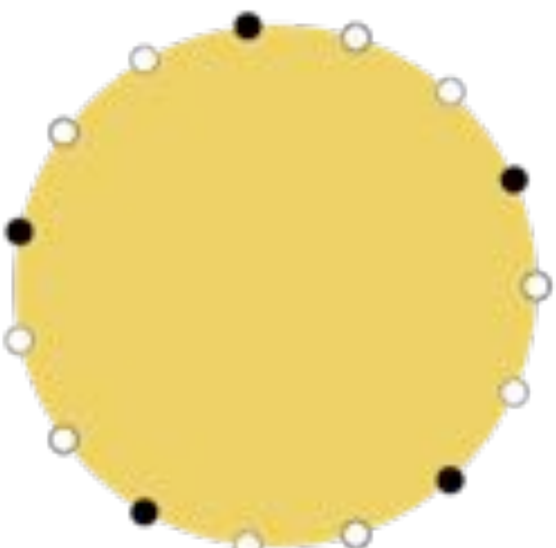
Maximally Even Sets



Diatonic scale:
{0, 2, 4, 5, 7, 9, 10}

Pentatonic scale:
{1, 3, 6, 8, 11}

Definition (Amiot, 2005) A set A with cardinality d given equal tempered space $\mathbf{Z}_c$ is maximally even if $|F_A(d)| \geq |F_B(d)|$ for all subsets B of cardinality d in $\mathbf{Z}_c$.

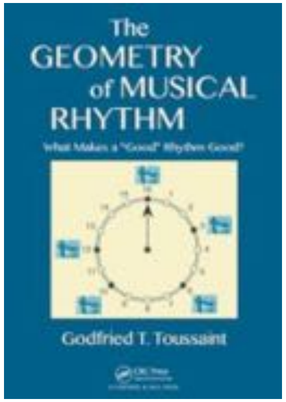


where $F_{set}(t) := \sum_{k \in set} e^{2i\pi kt/12}$

$$|F_A(5)| = 1+1+1+1+1 = 5$$

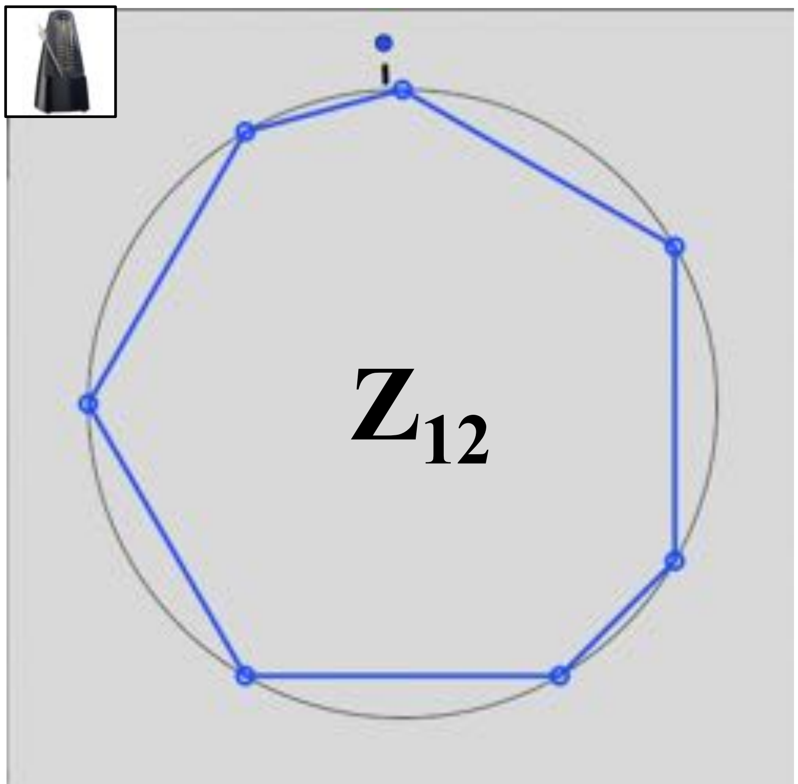
En général, $|F_A(t)| \leq \# A$

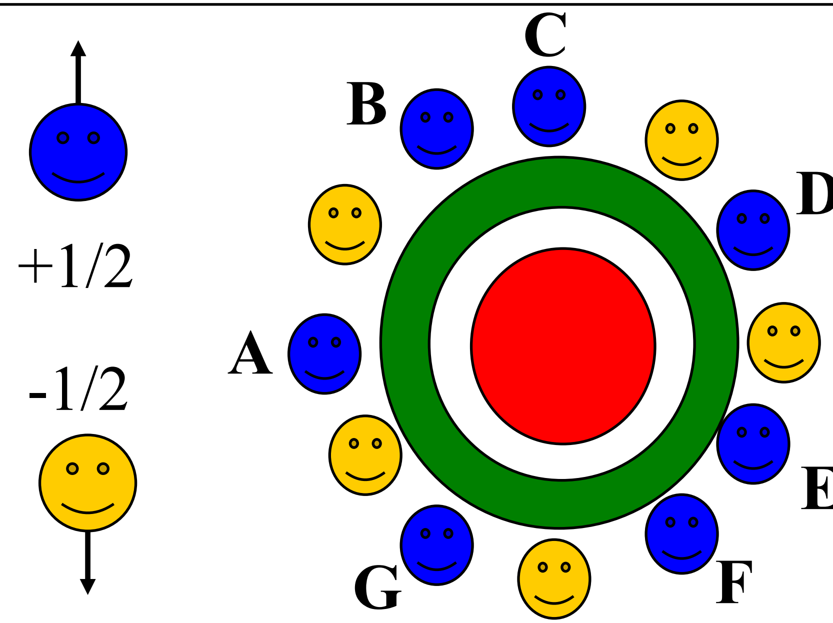
The pitch-rhythm isomorphic correspondence



"It is well known that there exists an isomorphic relation between pitch and rhythm, which several authors have pointed out from time to time."

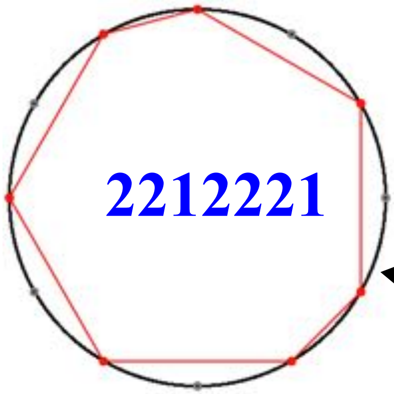
(G. Toussaint, *The geometry of musical rhythm. What makes a "Good" Rhythm Good?* CRC Press, 2013, p. xiii)

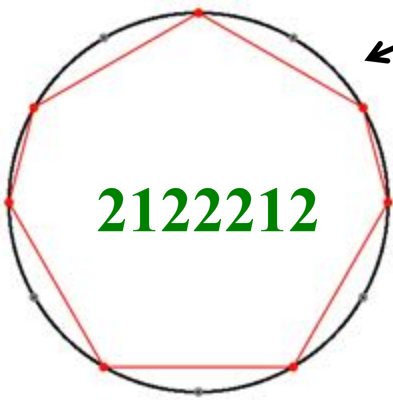




J. Douthett & R. Krantz, "Energy extremes and spin configurations for the one-dimensional antiferromagnetic Ising model with arbitrary-range interaction", *J. Math. Phys.* 37 (7), July 1996

The pitch-rhythm *cognitive* isomorphic correspondence





...

cyclic permutations

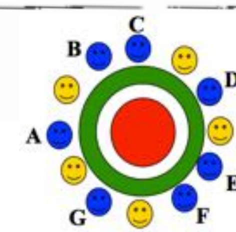
TABLE I

Comparison of M = 7, L = 12 patterns for pitch (scales) and rhythm (time-lines)

pattern	pitch domain name and notation (in C)	rhythm domain notation	examples from West Africa	references
1. 2212221	major scale (Ionian) CDEFGAB		Ewe (Atsiabek , Sogba, Atsia) also Yoruba	Jones (1959), C. K. Ladzekpo, S. K. Ladzekpo and Pantaleoni, Locke
2. 2122212	Dorian CDE♭ FGAB♭		Bemba—Northern Rhodesia	Jones (1965), (Ekwueme)
3. 1222122	Phrygian CD♭ E♭ FGA♭ B♭		———	———
4. 2221221	Lydian CDEF#GAB		Ga-Adangme (common) also common Haitian pattern, Akan (Ab fo)	C. K. Ladzekpo, Combs (1974), R. Hill, Asiama
5. 2212212	Mixolydian CDEFGAB♭		Yoruba sacred music from Ekiti	King
6. 2122122	Aeolian CDE♭ FGA♭ B♭		Ashanti (Ab fo , Mpre)	Koetting
7. 1221222	Locrian CD♭ E♭ FG♭ A♭ B♭		Ghana*	Nketia (1963a)
8. 2121222	(#2 Locrian) CDE♭ FG♭ A♭ B♭		Ashanti (Asedua)	C. K. Ladzekpo
9. 2112123	——— CDD#EF#GA		Akan (juvenile song)	Nketia (1963b)

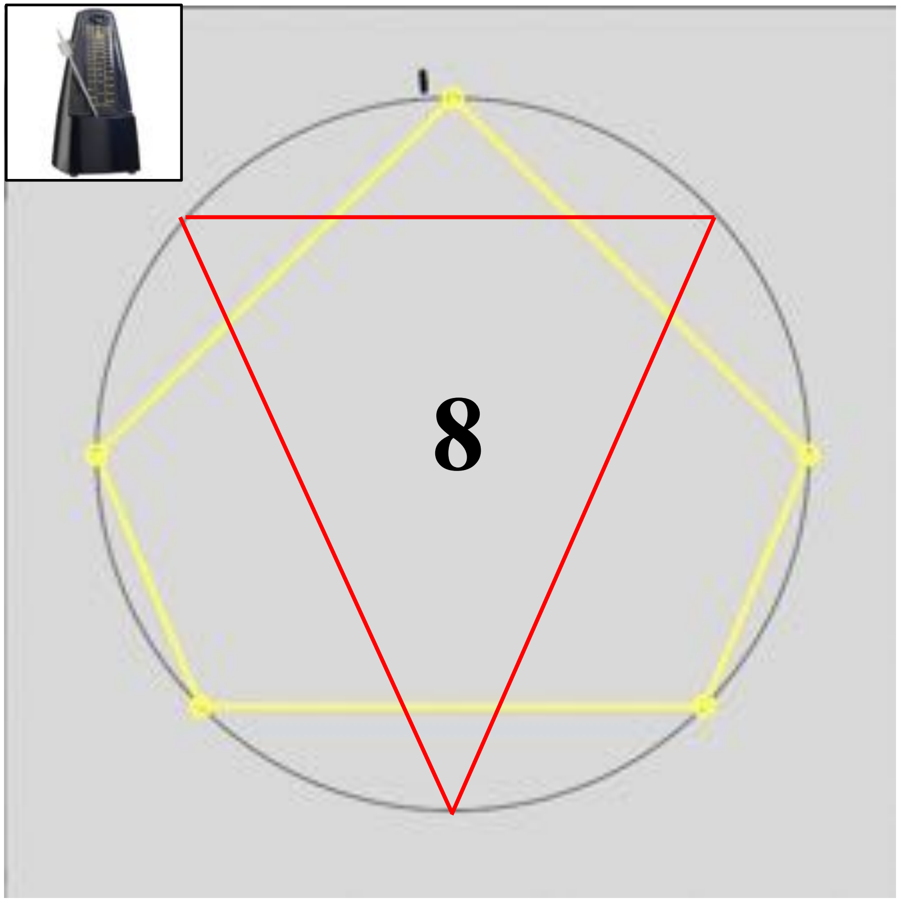
* clap pattern
† mute stroke on bell

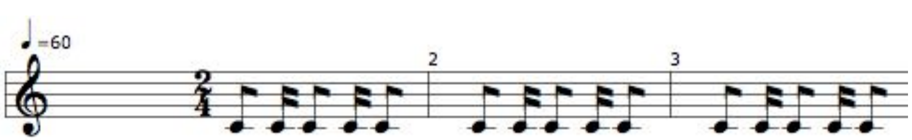
J. Pressing, "Cognitive isomorphisms between pitch and rhythm in world musics: West Africa, the Balkans and Western tonality", *Studies in Music*, 17, p. 38-61



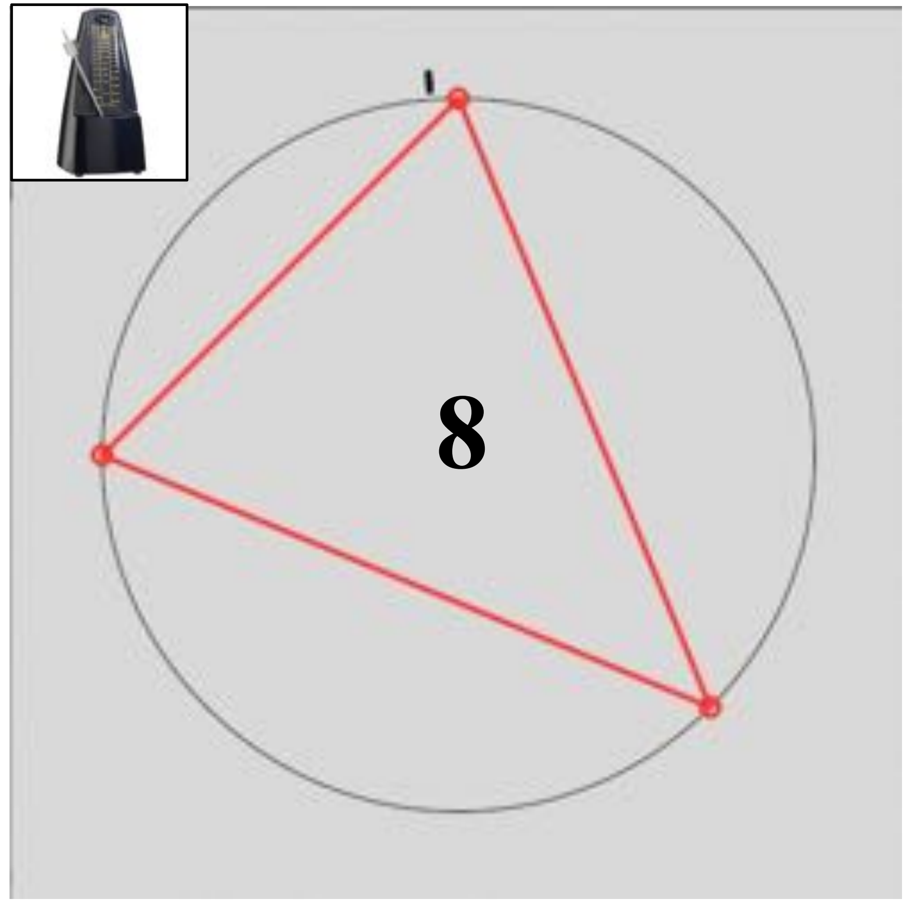
African-cuban ME-rhythms

El cinquillo

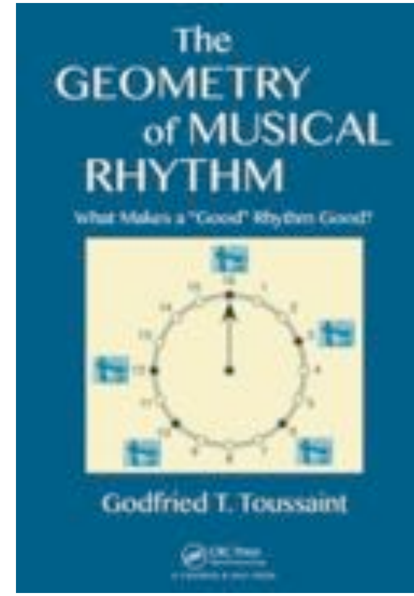


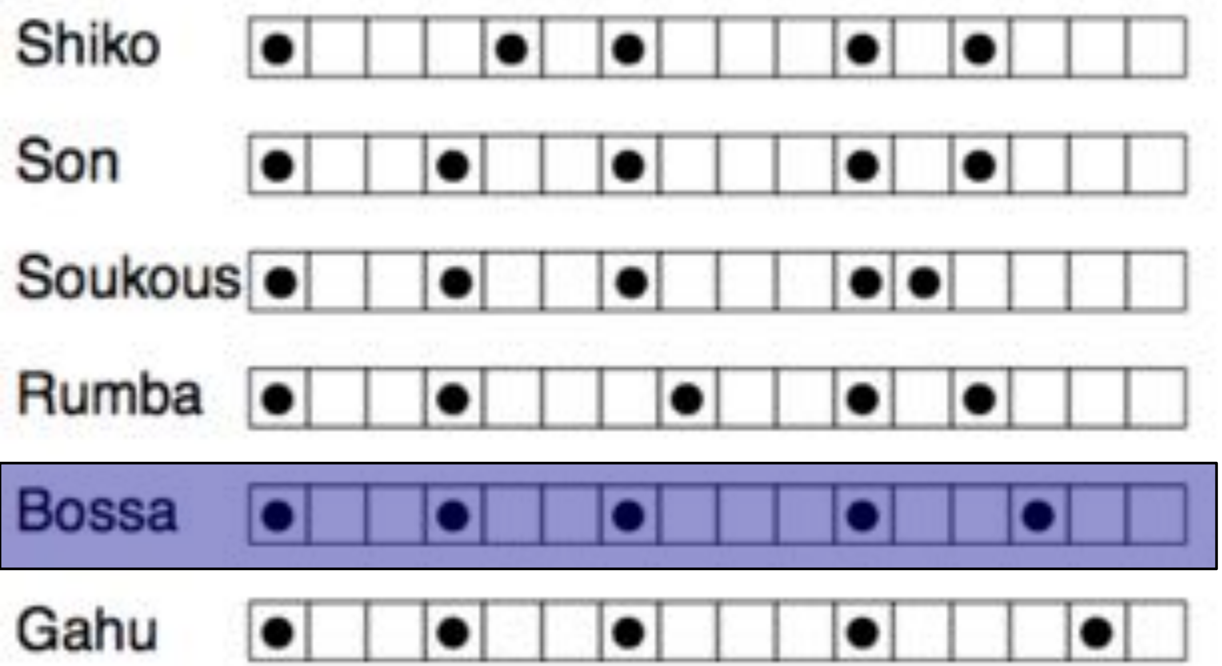


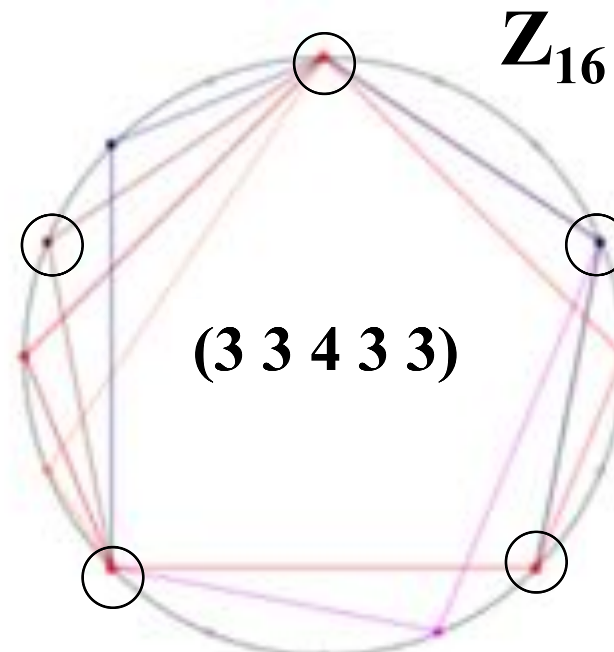
El trecillo



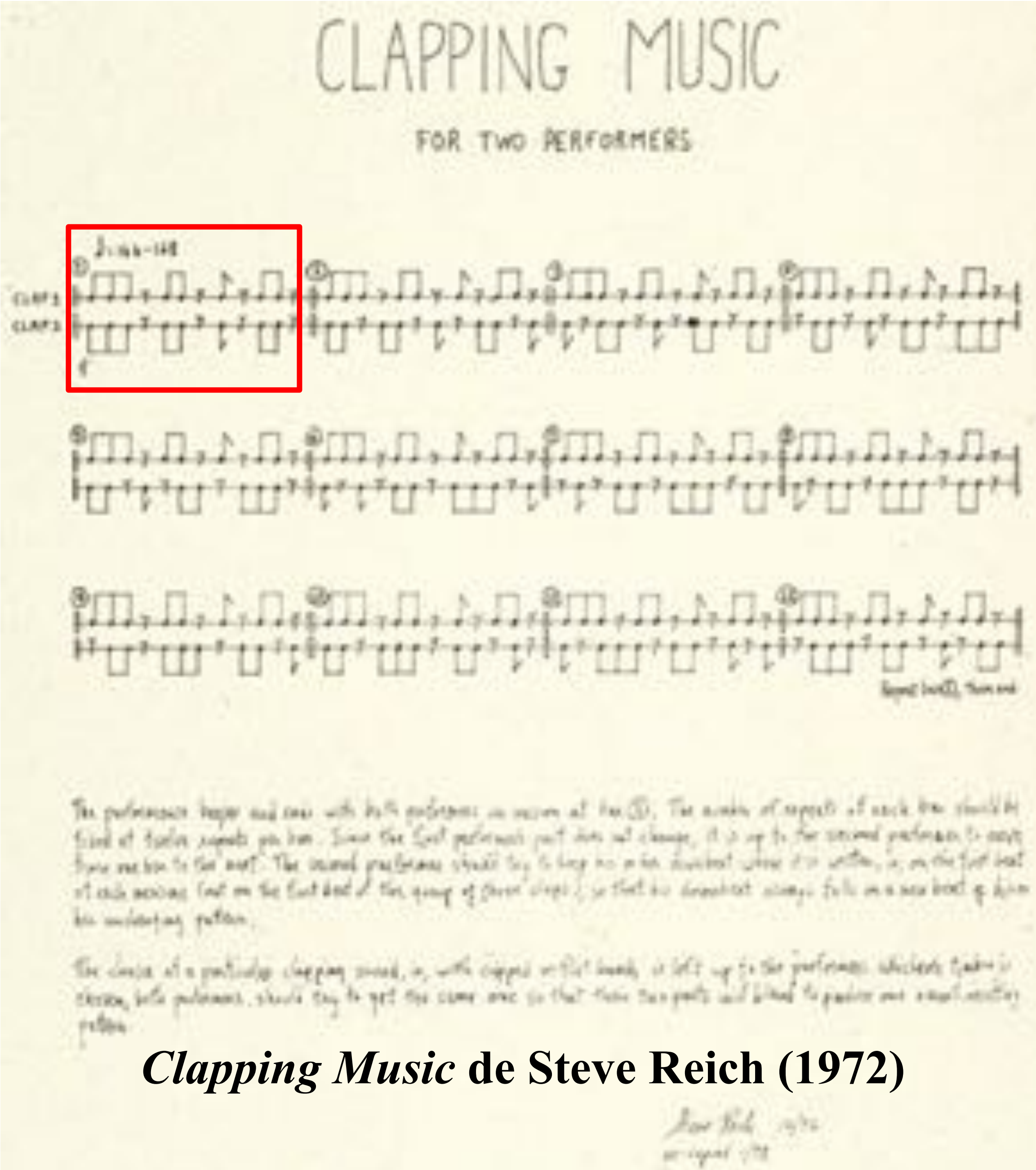
The geometry of African-Cuban rhythms



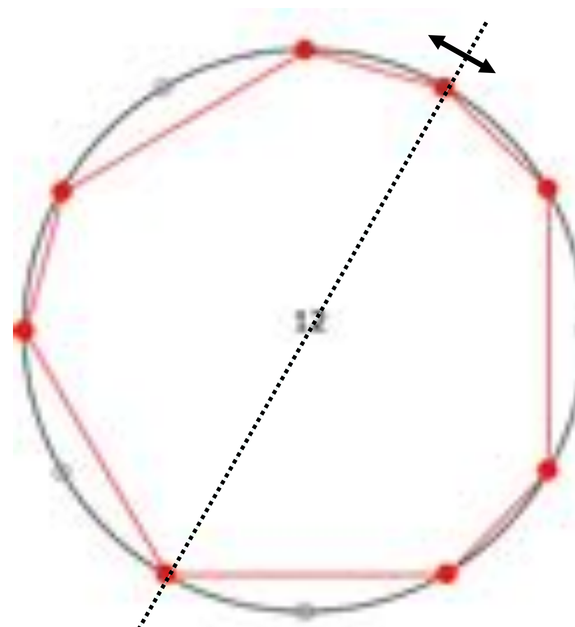




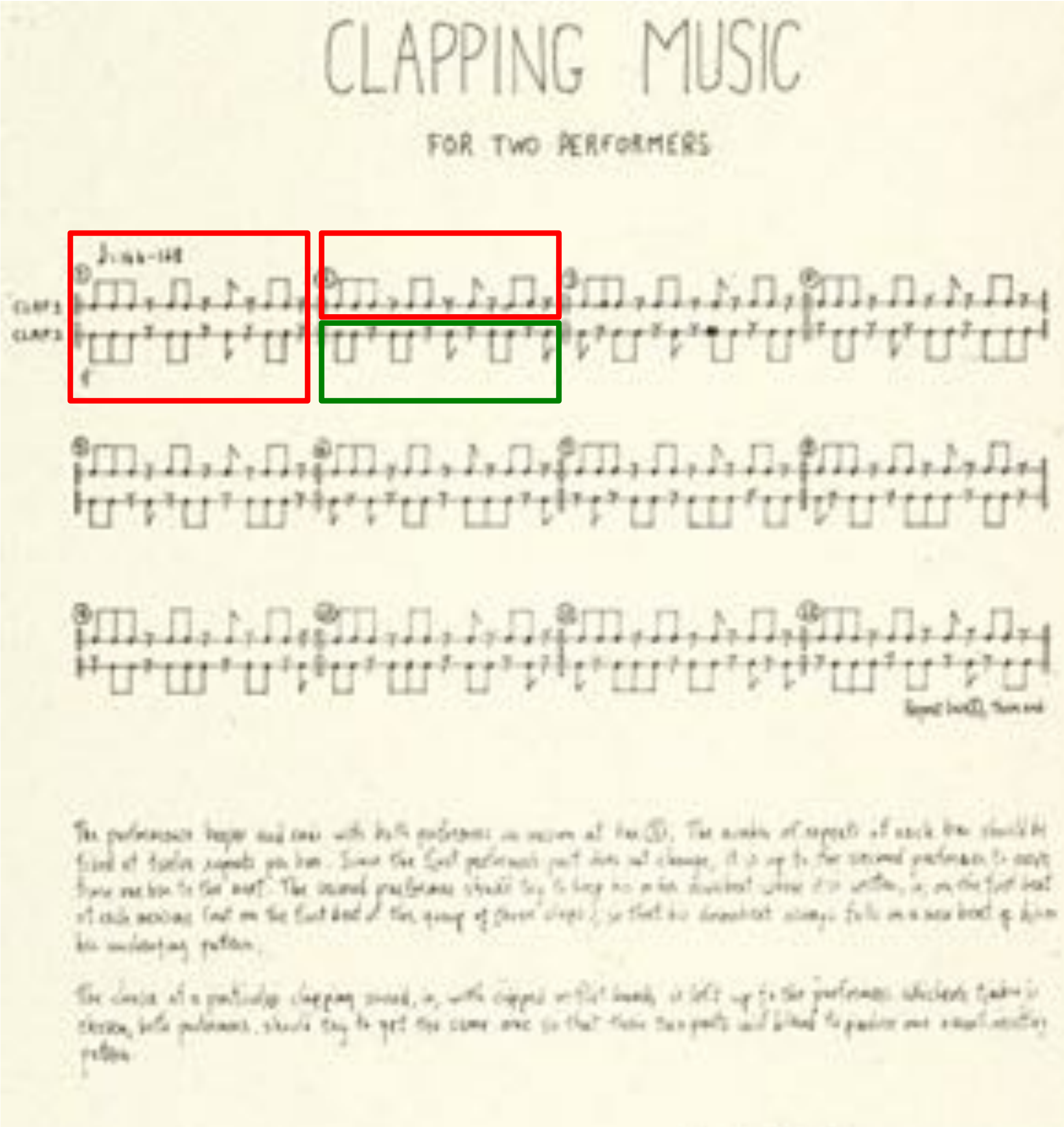
Palindromic structures in Steve Reich's music



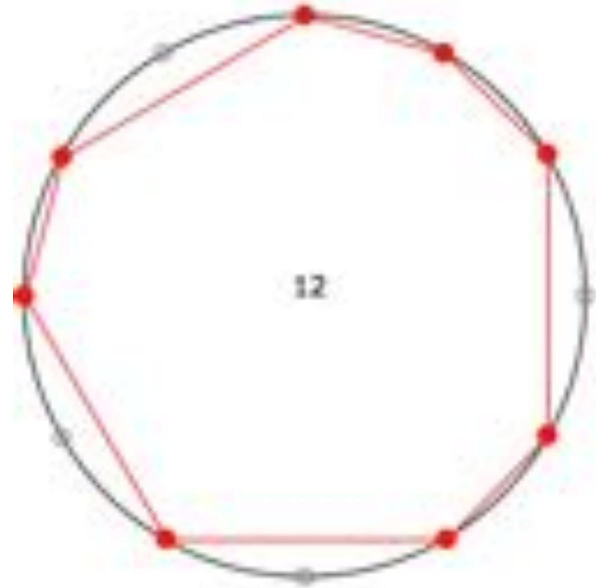
Clapping Music de Steve Reich (1972)

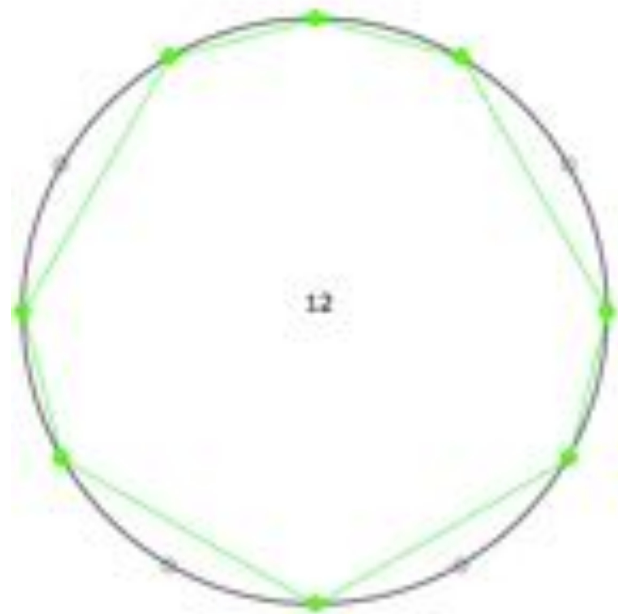


The circle and its ‘canonic’ rotations

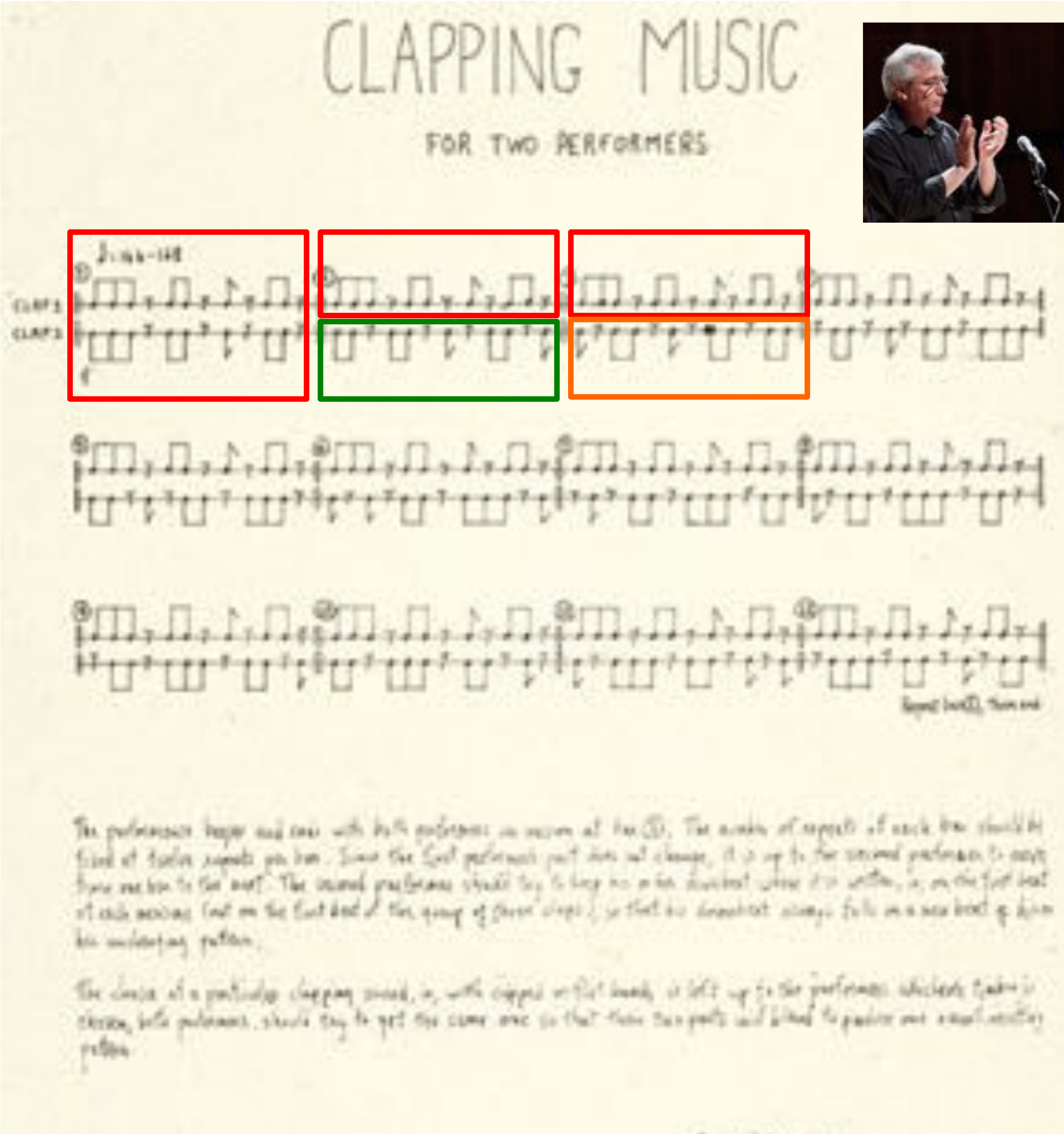


Clapping Music (1972)

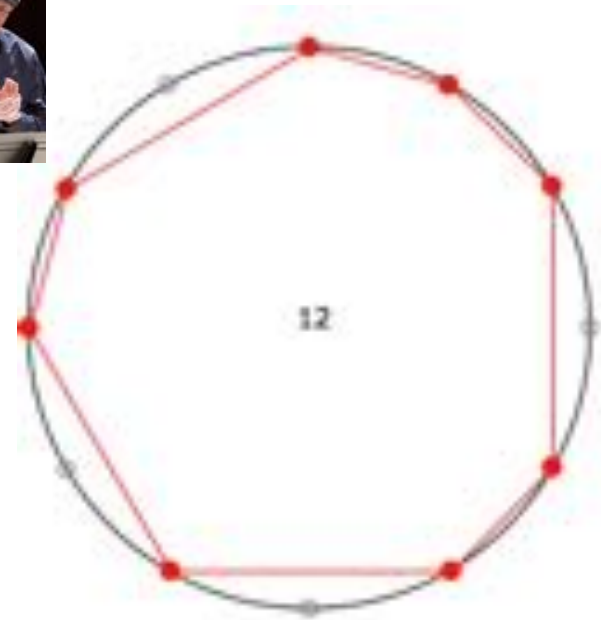




The circle and its ‘canonic’ rotations

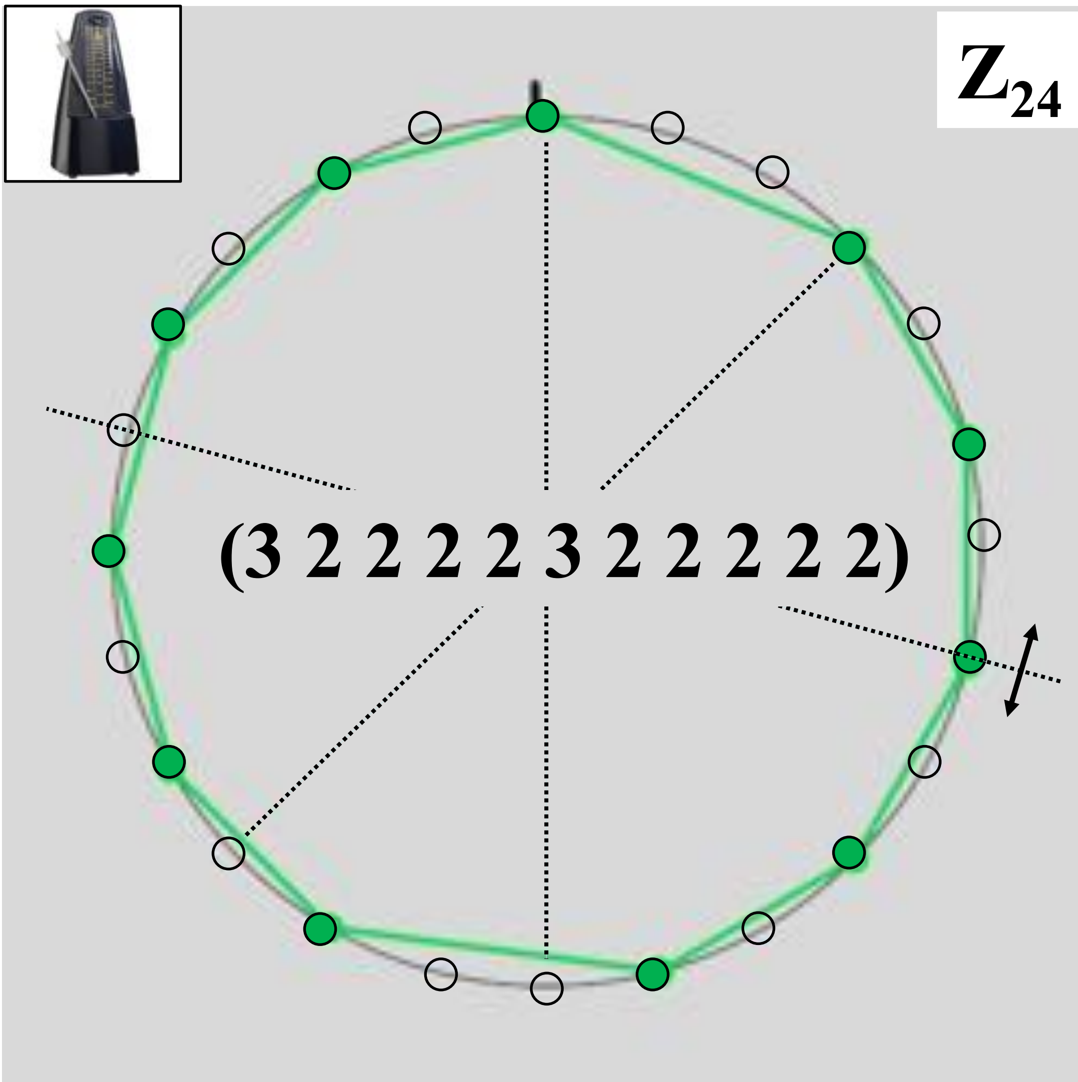


Clapping Music (1972)



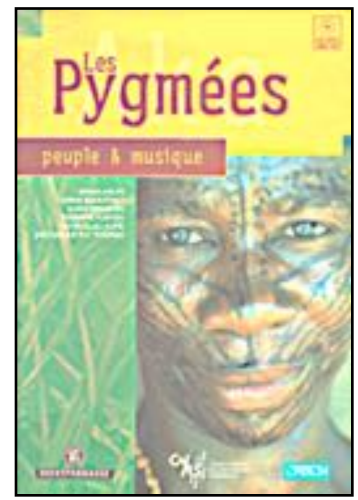
Gerubach's Scrolling Score Project
http://www.gerubach.com

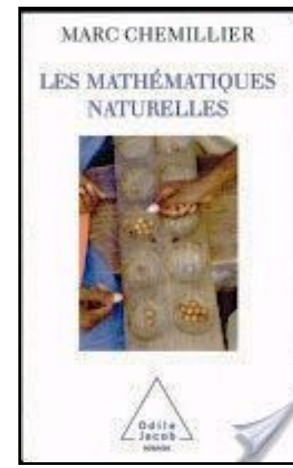
Odditive property of orally-trasmitted practices



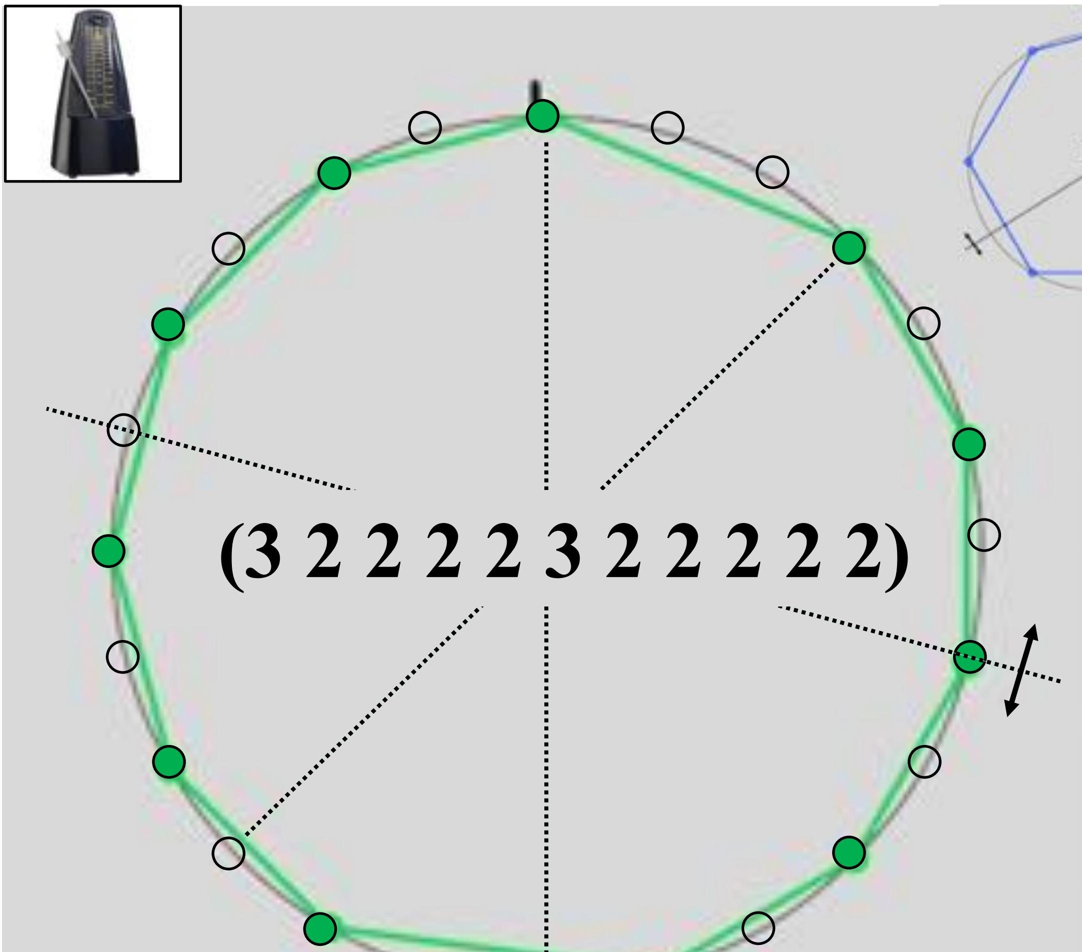
Simha Arom

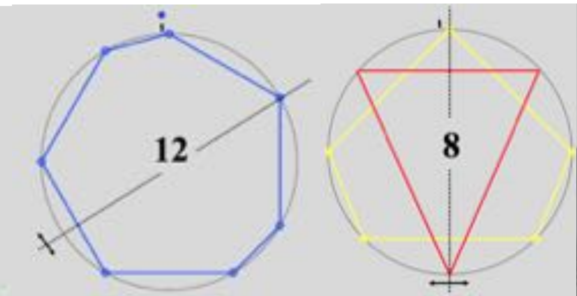
Marc Chemillier



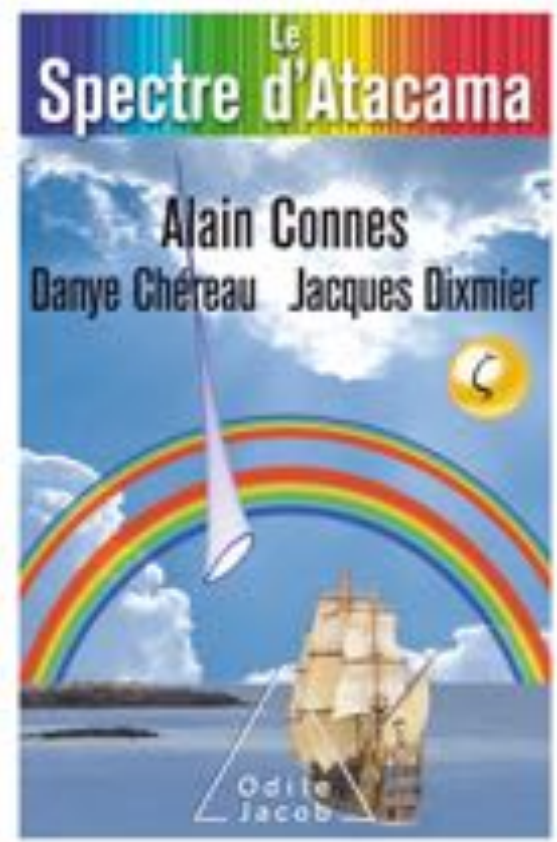


Olivier Messiaen's non-invertible rhythms





Olivier Messaien

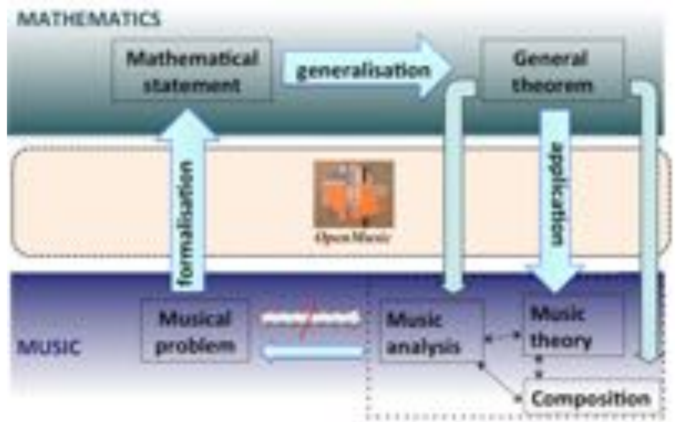


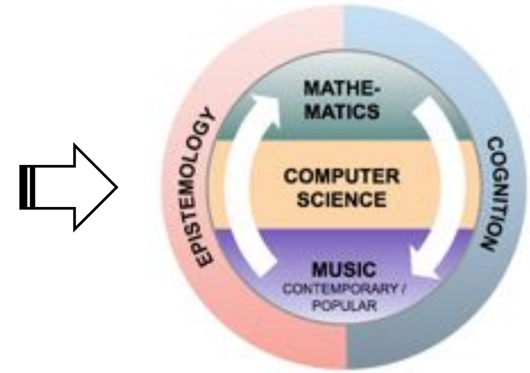
Alain Connes

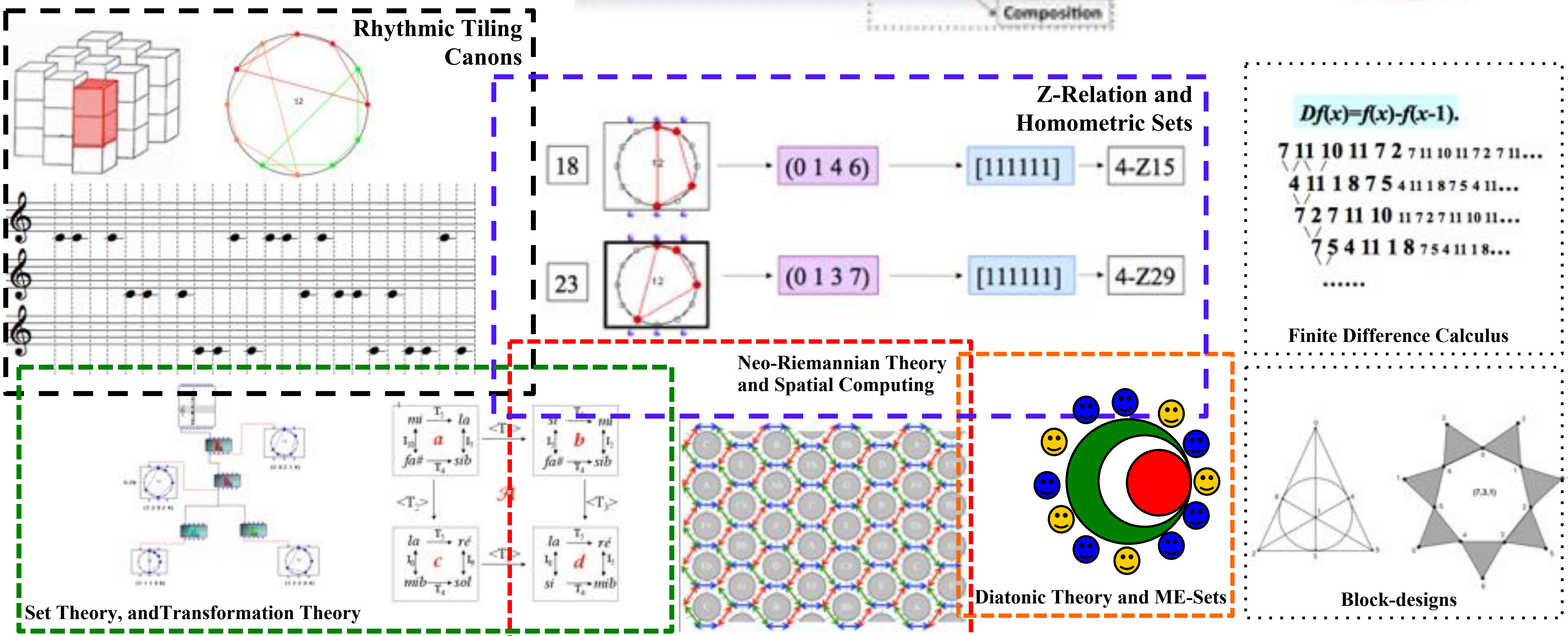
A short catalogue of mathemusical problems

M. Andreatta : *Mathematica est exercitium musicae*, Habilitation Thesis, IRMA University of Strasbourg, 2010

- **Tiling Rhythmic Canons**
- ***Z* relation and homometry**
- **Transformational Theory**
- **Music Analysis, SC and FCA**
- **Diatonic Theory and ME-Sets**
- **Periodic sequences and FDC**
- **Block-designs in composition**

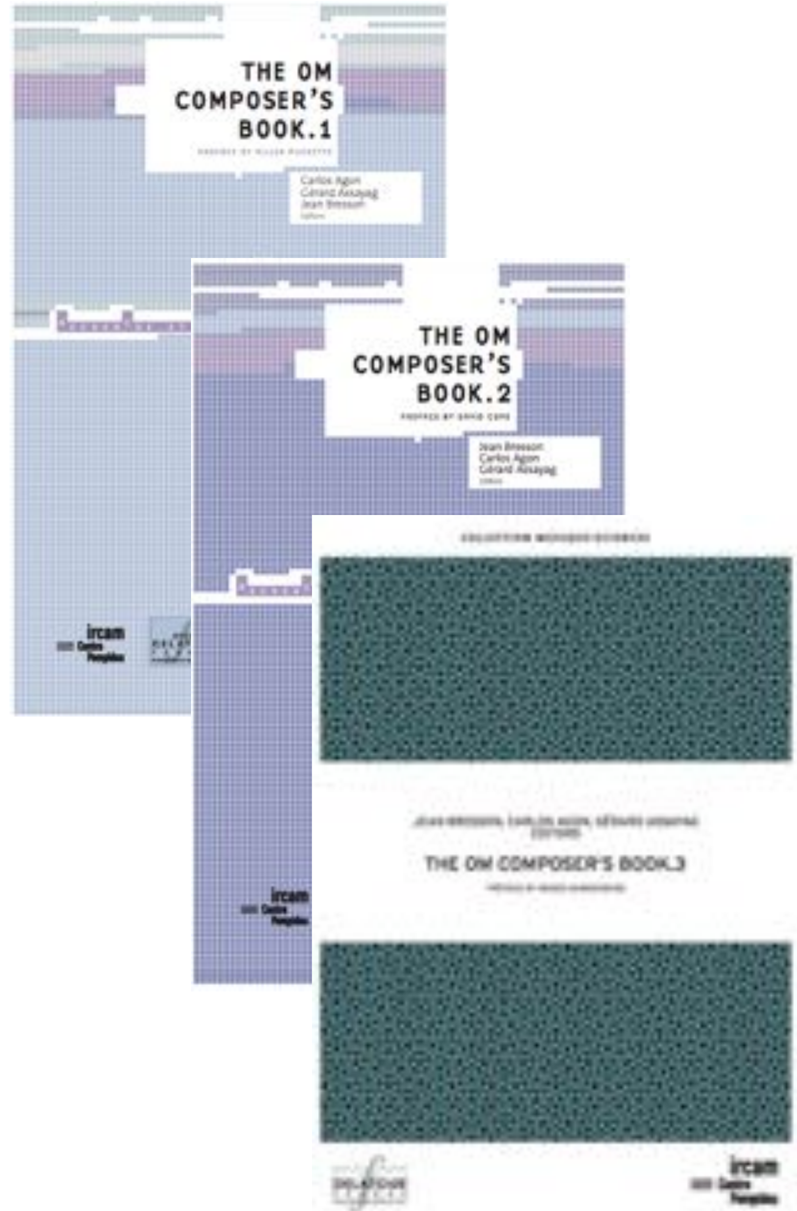






OpenMusic, a Visual Programming Language for computer-aided composition

`www.repmus.ircam.fr/openmusic/home`



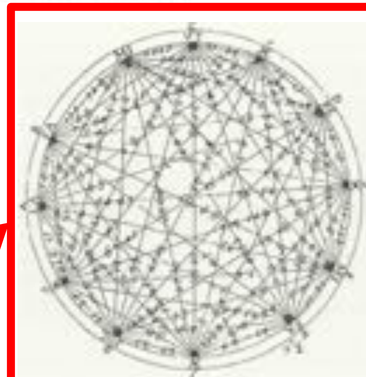
C. Agon, G. Assayag and J. Bresson, *The OM Composer's Book* (3 volumes)
"Musique/Sciences" Series, Ircam/Delatour, 2006, 2007 and 2016

Music and mathematics: « prima la musica »!

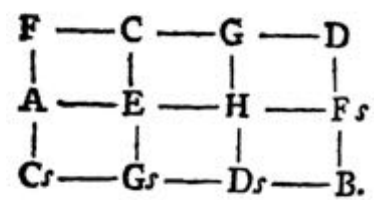
MUSIC	MATHS
500 B.C. Pitches and lengths of strings are related. Here **music** gives a marvelous thrust to **number theory** and **geometry**.	Discovery of the fundamental importance of **natural numbers** and the invention of **fractions**.
No correspondence in music.	Positive irrational numbers [...]
300 B.C. [...] Music theory highlights the discovery of the **isomorphism between the logarithms** (musical intervals) and **exponentials** (string lengths) more than 15 centuries before their discovery in mathematics; also a **premonition of group theory** is suggested by Aristoxenos.	No reaction in mathematics. [...]
1000 A.D. Invention of the **two-dimensional spatial representation of pitches** linked with time by means of staves and points [...] seven centuries (1635-37) before the magnificent **analytical geometry** of Fermat and Descartes.	*No parallel in mathematics.*
1500 *No response or development of the preceding concepts.*	Zero and negative numbers are adopted. Construction of the set of rationals.
1600 *No equivalence, no reaction.*	The sets of real numbers and of logarithms are invented.
1648 Invention of **musical combinatorics** by Marin Mersenne (*Harmonicorum Libri*)	Probability theory by Bernoulli (*Ars Conjectandi*, 1713)
1700 [...] The **fugue**, for example, is an **abstract automaton** used two centuries before the birth of the science of automata. Also, there is an **unconscious manipulation of finite groups** (Klein group) in the four variations of a melodic line used in counterpoint.	Number theory is ahead of but has no equivalent yet in temporal structures. [...]
1773 A first **geometric** and **graph-theoretic** representation of pitches (*Speculum Musicum*)	Invention of graph theory
1900 Liberation from the tonal yoke. First acceptance of the neutrality of chromatic totality (Loquin [1895], Hauer, Schoenberg).	The infinite and transfinite numbers (Cantor). Peano axiomatics. [...] The beautiful measure theory (Lebesque, ...)
1920 First radical formalization of macrostructures through the serial system of Schoenberg.	No new development of the number theory.
1929 and **1937-1939** Susanne K. Langer and Ernst Krenek on the role of axioms in music	David Hilbert, *Die Grundlage der Geometrie* (1899)
1946 Milton Babbitt on group theory and integral serialism	Rudolf Carnap, *The Logical Syntax of Language* (1937)

I. Xenakis

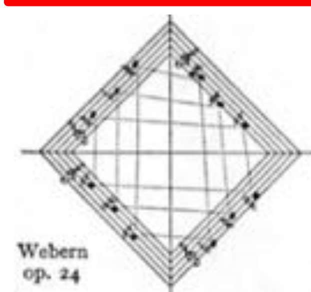
Pythagoras and the monochord, VIth-Vth Century B.C.



Mersenne and the 'musical clock', 1648

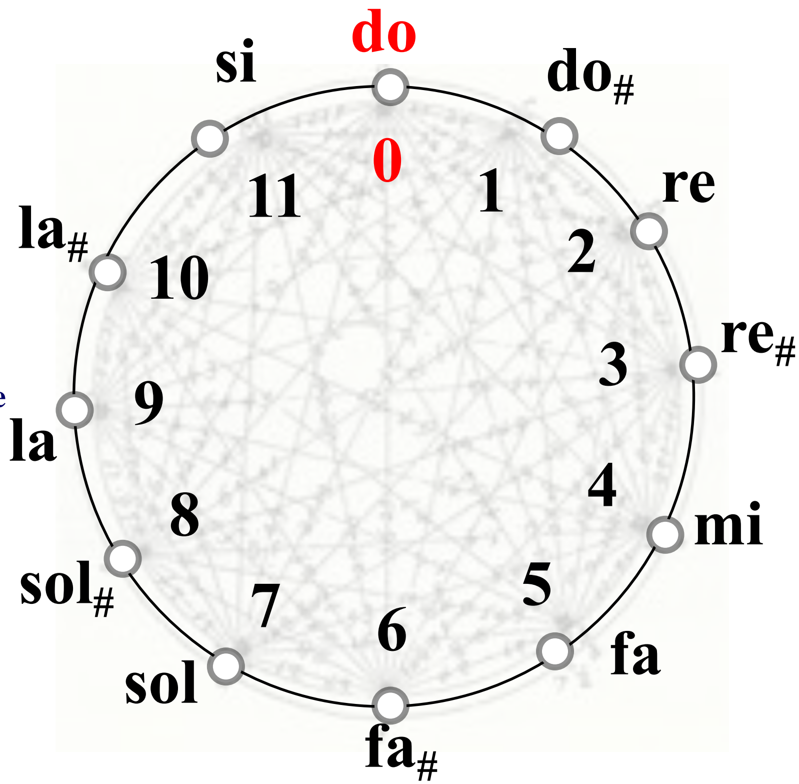


Euler and the *Speculum musicum*, 1773



The circular representation of the pitch space

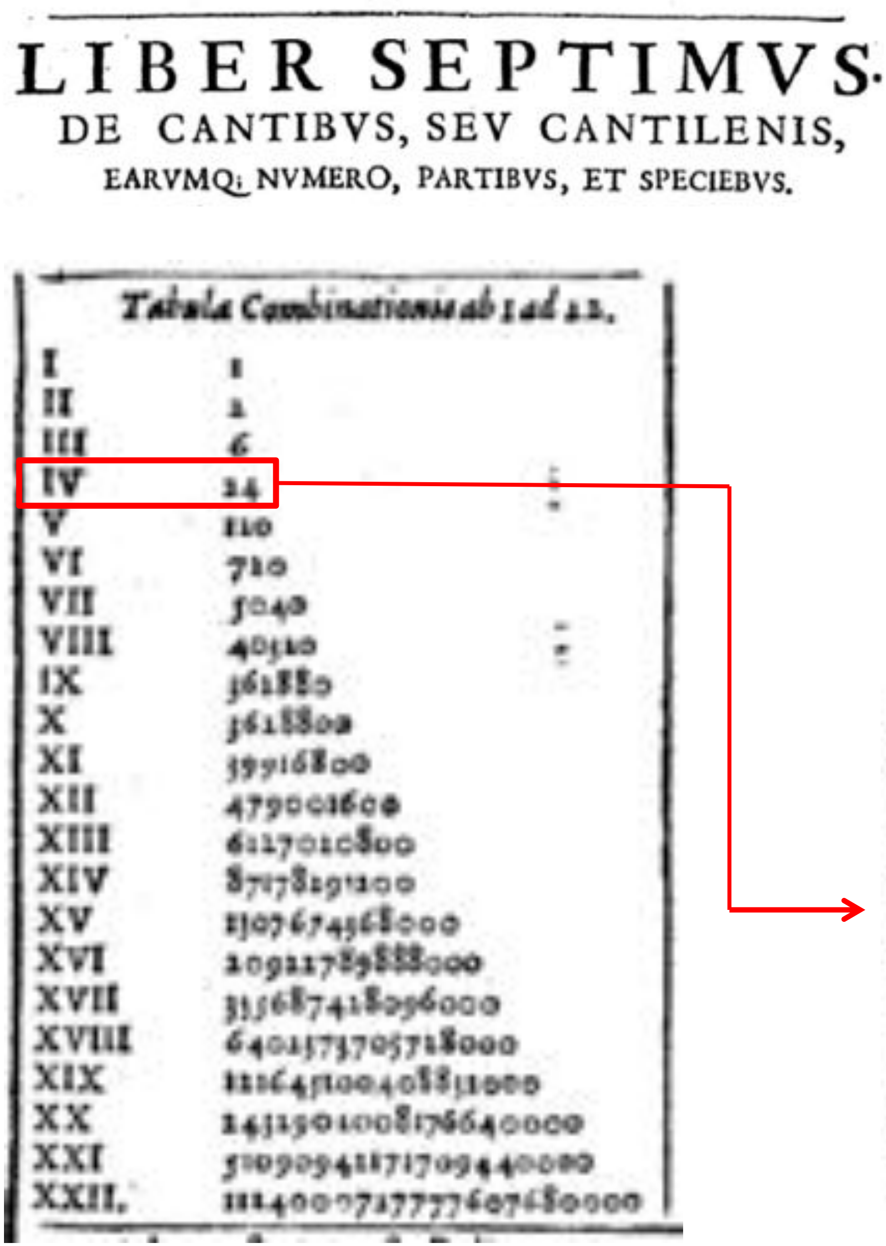
Marin Mersenne



Harmonicorum Libri XII, 1648

Permutational strategies in contemporary music

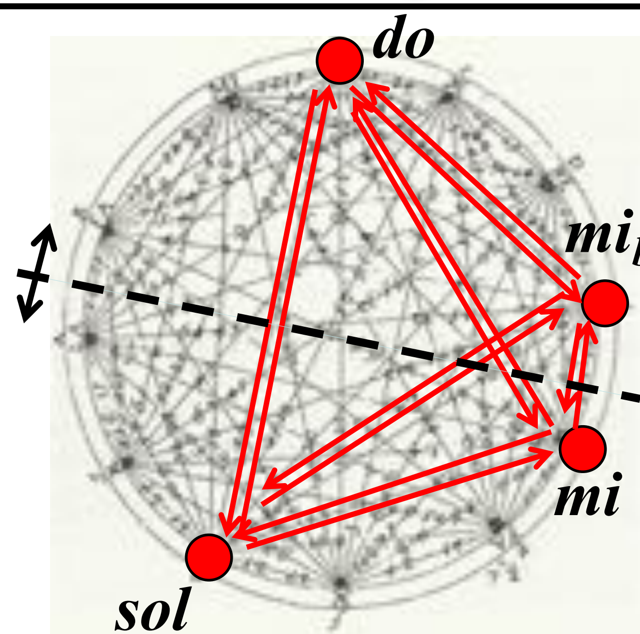
114 Marin Mersenne, *Harmonicorum Libri XII*, 1648

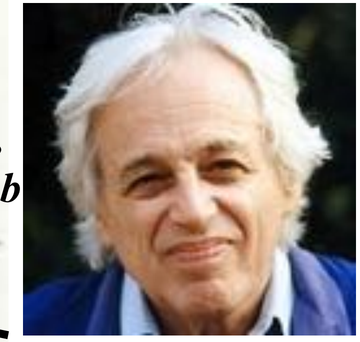


LIBER SEPTIMVS
DE CANTIBVS, SEV CANTILENIS,
EARVMQ; NVMERO, PARTIBVS, ET SPECIEBVS.

Tabula Combinationis ab 1 ad 22.

I	1
II	2
III	6
IV	24
V	120
VI	720
VII	5040
VIII	40320
IX	362880
X	3628800
XI	39916800
XII	479001600
XIII	6227020800
XIV	87178291200
XV	1307674368000
XVI	20922789888000
XVII	355687428096000
XVIII	6402373705728000
XIX	121645100408832000
XX	2432902008176640000
XXI	51090942171709440000
XXII.	1124000727777607680000

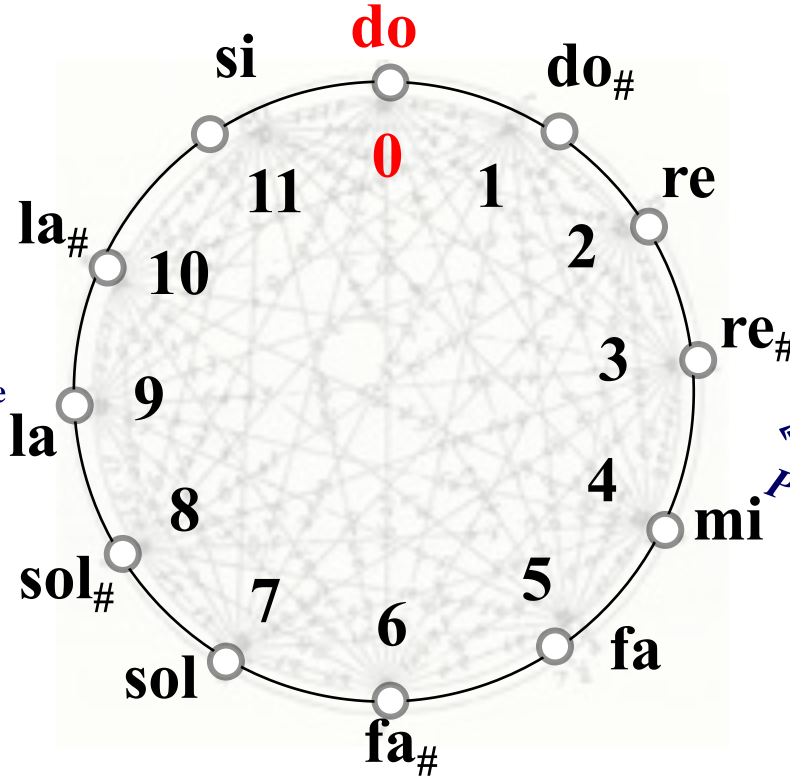




Six Bagatelles
(G. Ligeti, 1953)

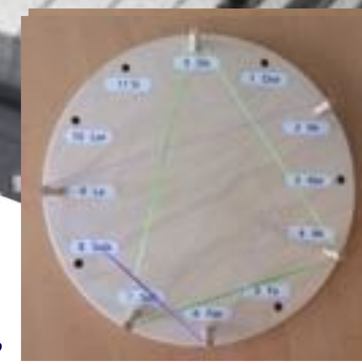
The circular representation of the pitch space

Marin Mersenne



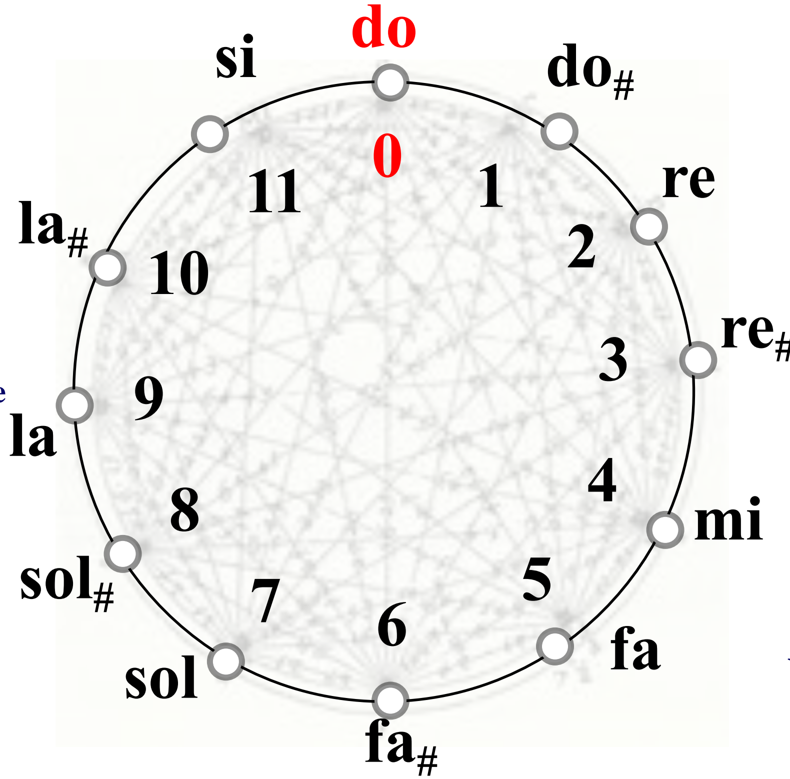
Harmonicorum Libri XII, 1648

M. Andreatta, C. Agon, «La musique mise en algèbre», *Pour la Science*, 2008



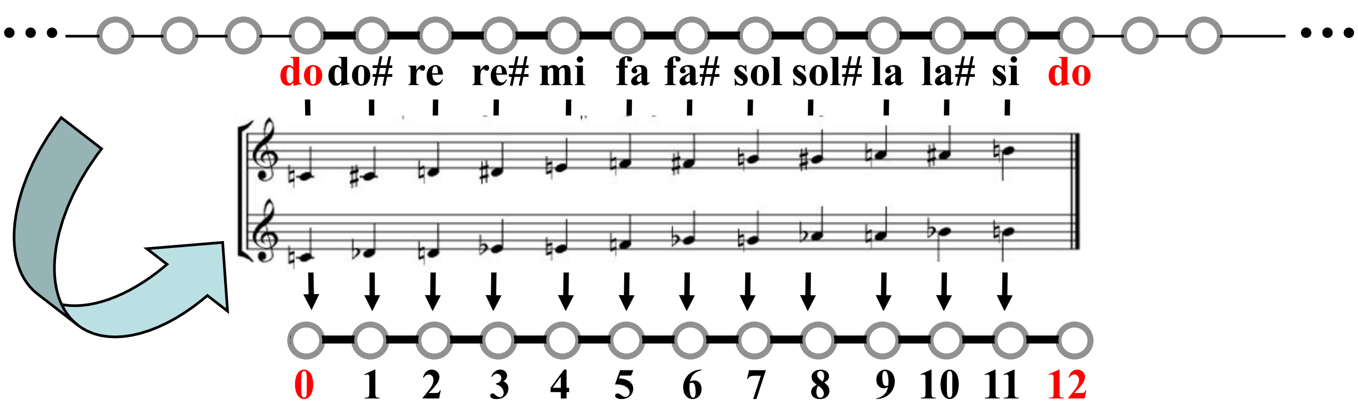
The circular representation of the pitch space

Marin Mersenne



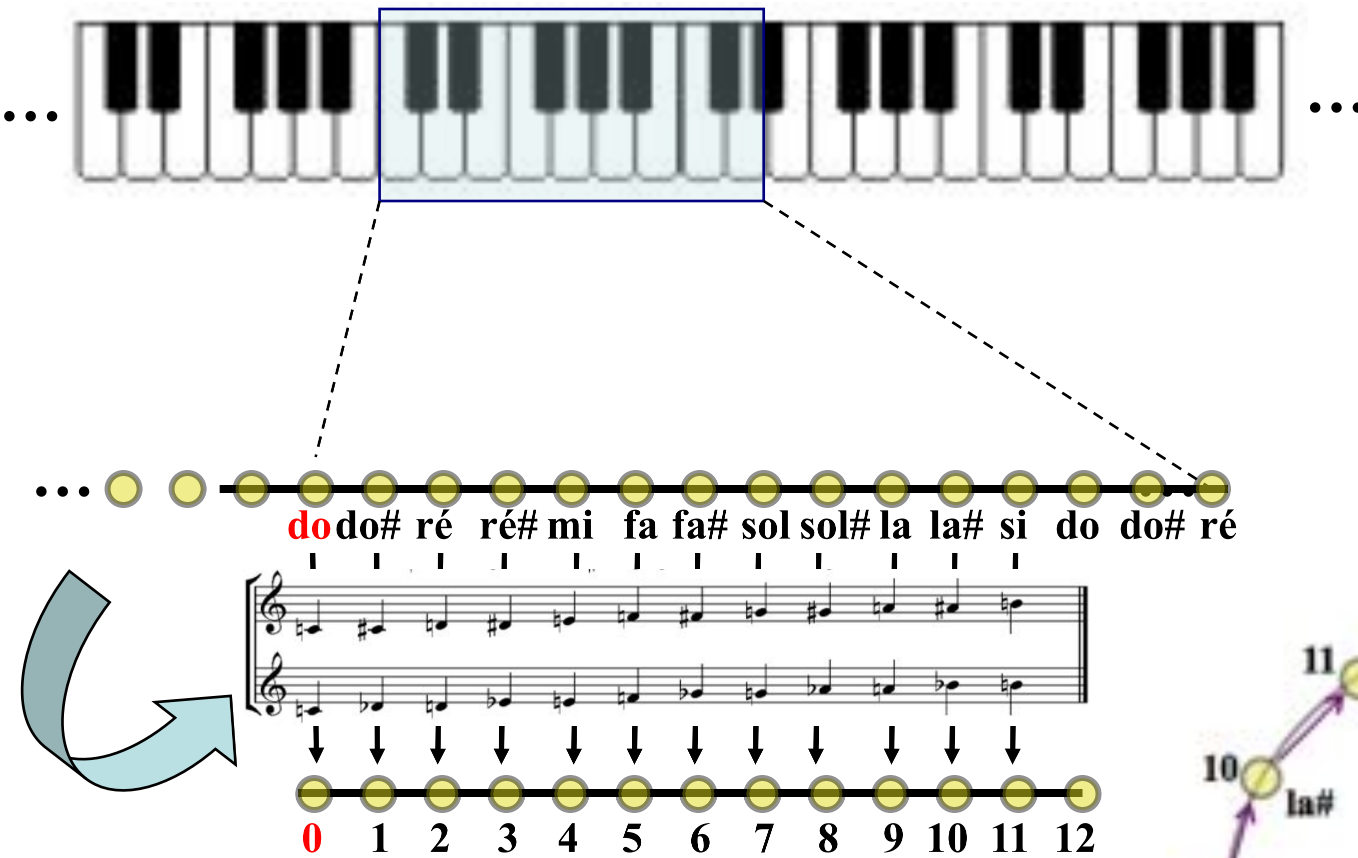
Harmonicorum Libri XII, 1648

M. Andreatta, C. Agon, « Algèbre et géométrie : sont-elles inscrites dans le cerveau ? », Pour la Science, 2018



→ DEMO

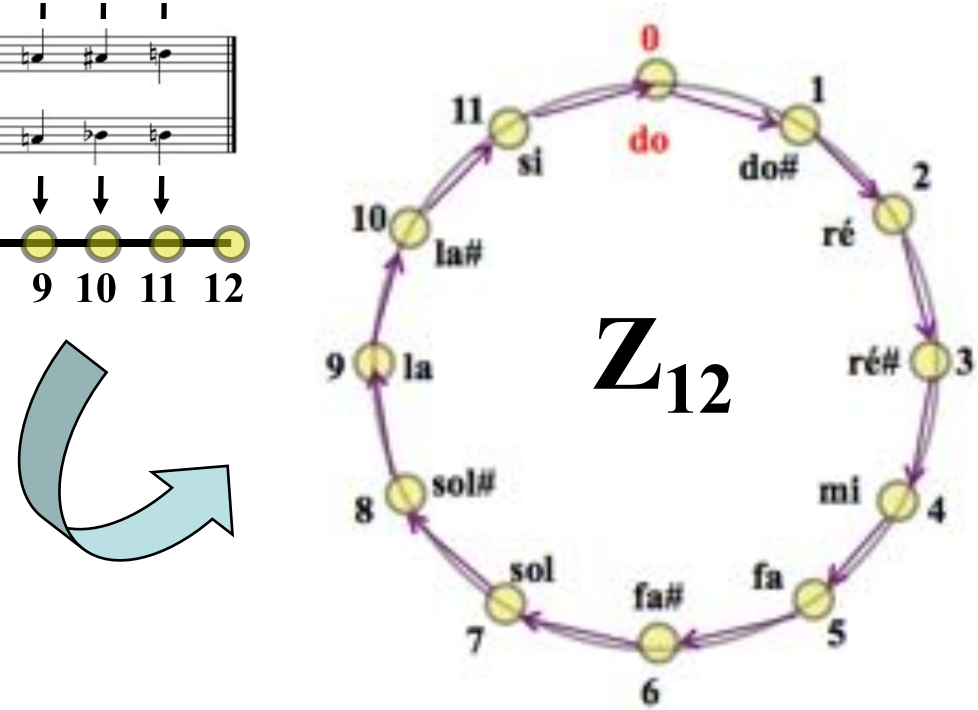
The equal tempered space is a cyclic group



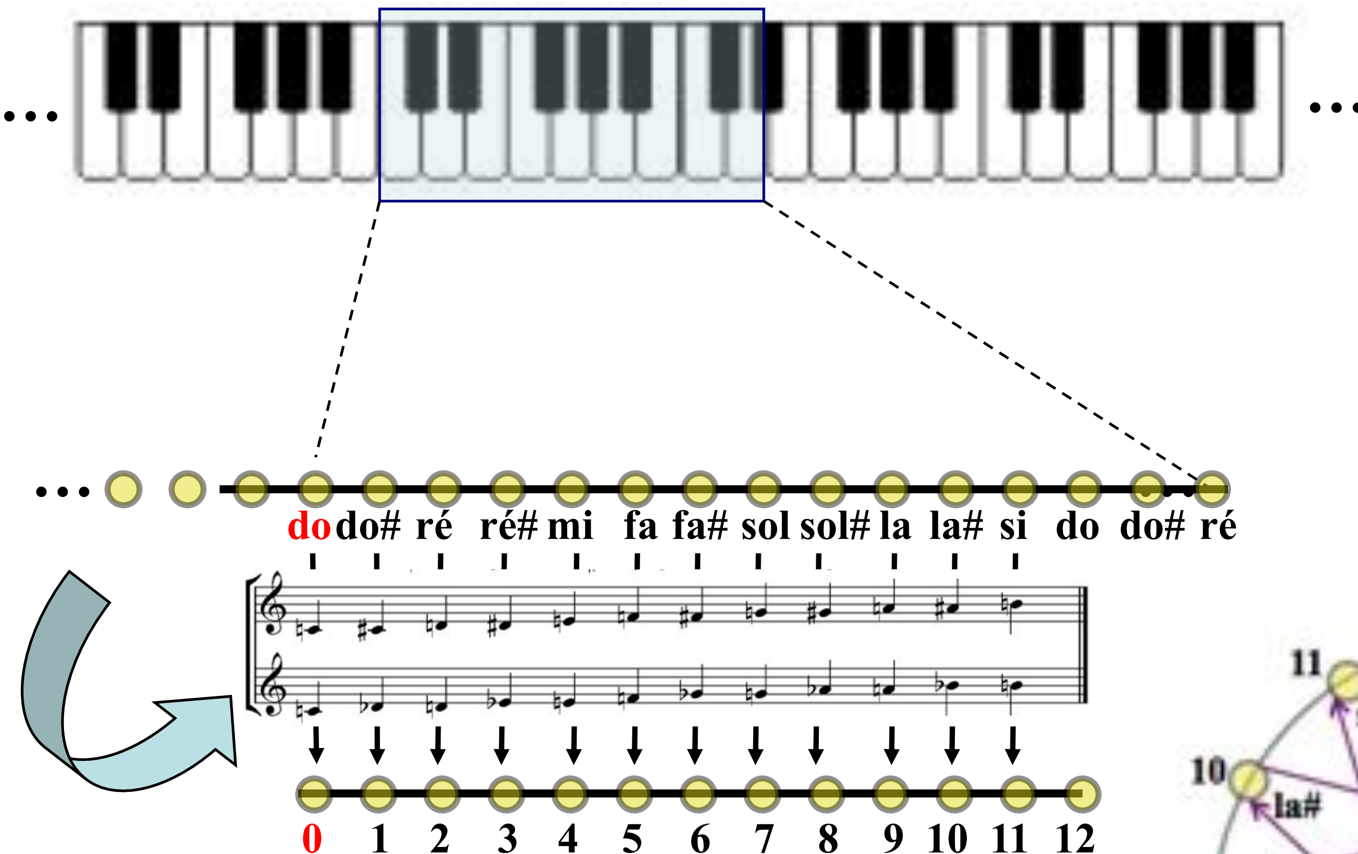
The generators of the cyclic group of order 12 are the transpositions T_1, T_5, T_7 et T_{11} where

$T_k : x \rightarrow x+k \bmod 12$

$$Z_{12} = < T_1 \mid (T_1)^{12} = T_0 >$$



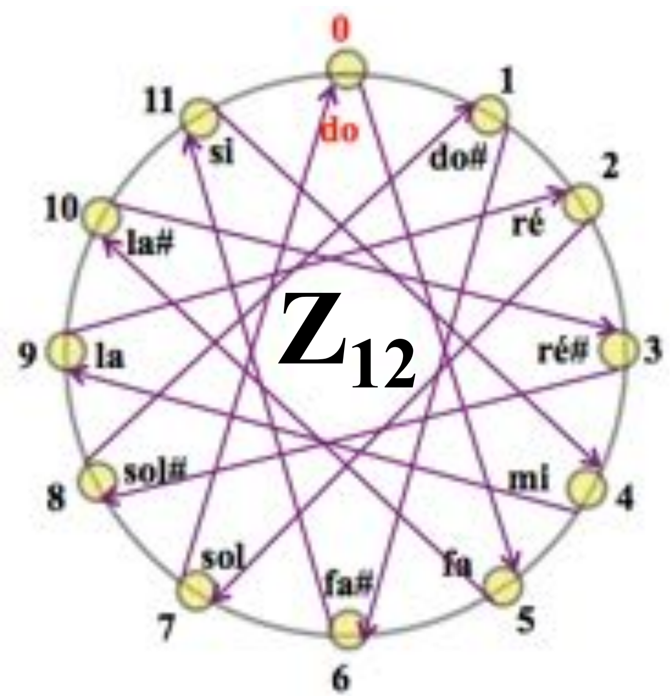
The equal tempered space is a cyclic group



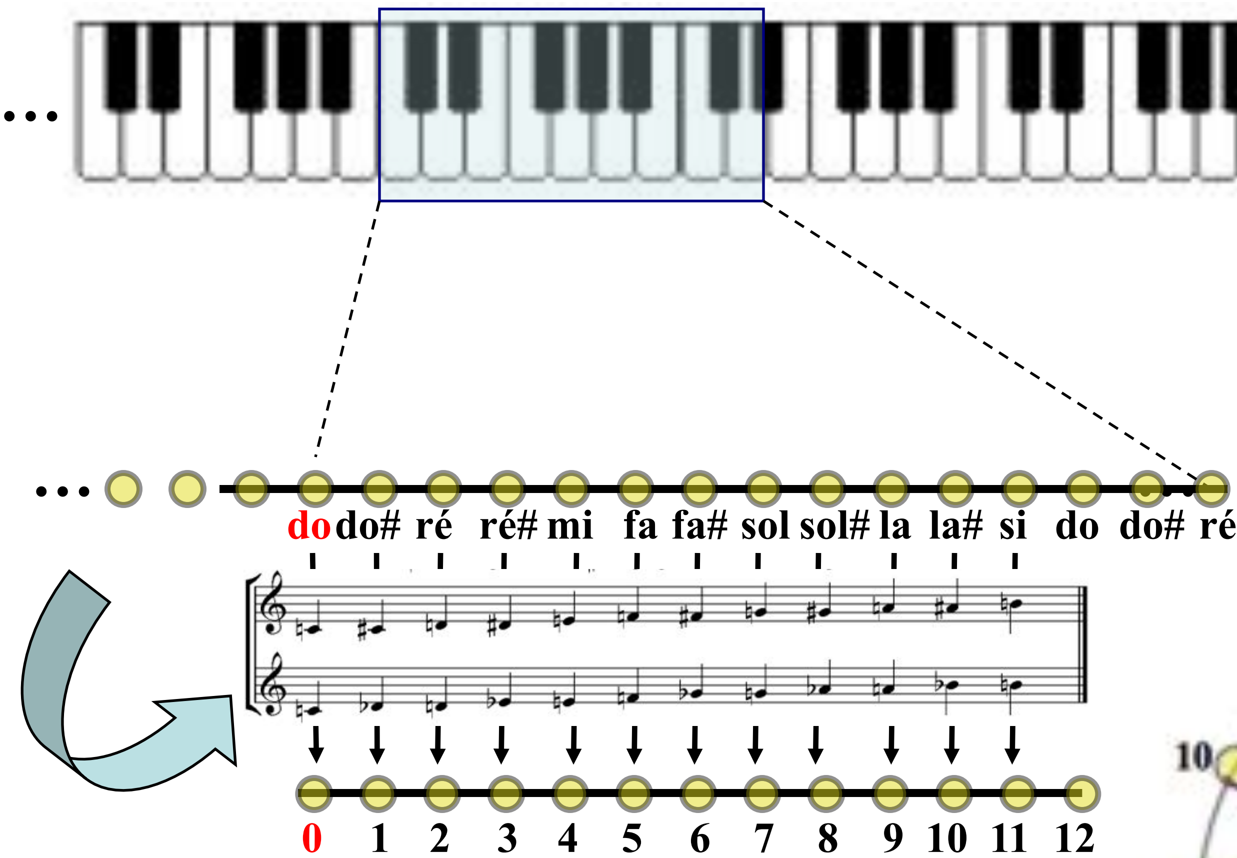
The generators of the cyclic group of order 12 are the transpositions T_1, T_5, T_7 et T_{11} where

$T_k: x \to x+k \bmod 12$

$$Z_{12} = < T_1 \mid (T_1)^{12} = T_0 > =$$
$$= < \mathbf{T_5} \mid (\mathbf{T_5})^{12} = \mathbf{T_0} >$$

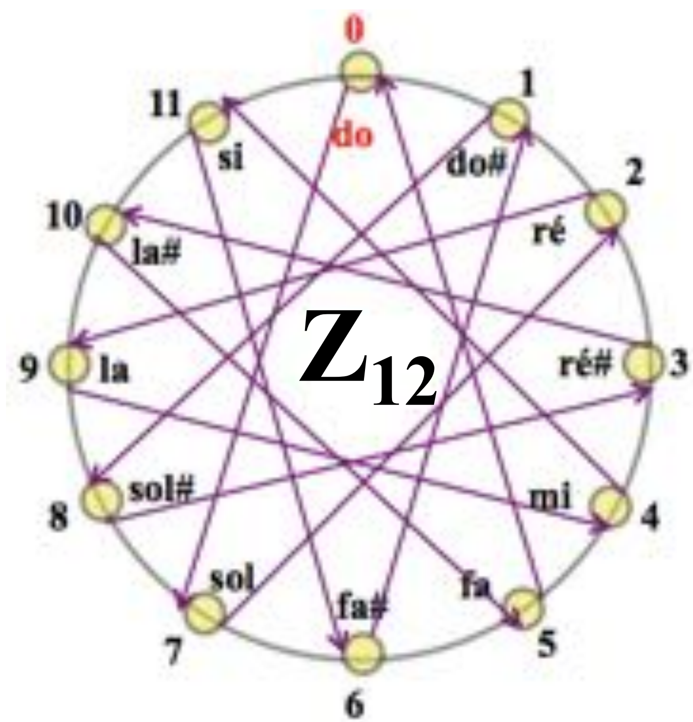


The equal tempered space is a cyclic group

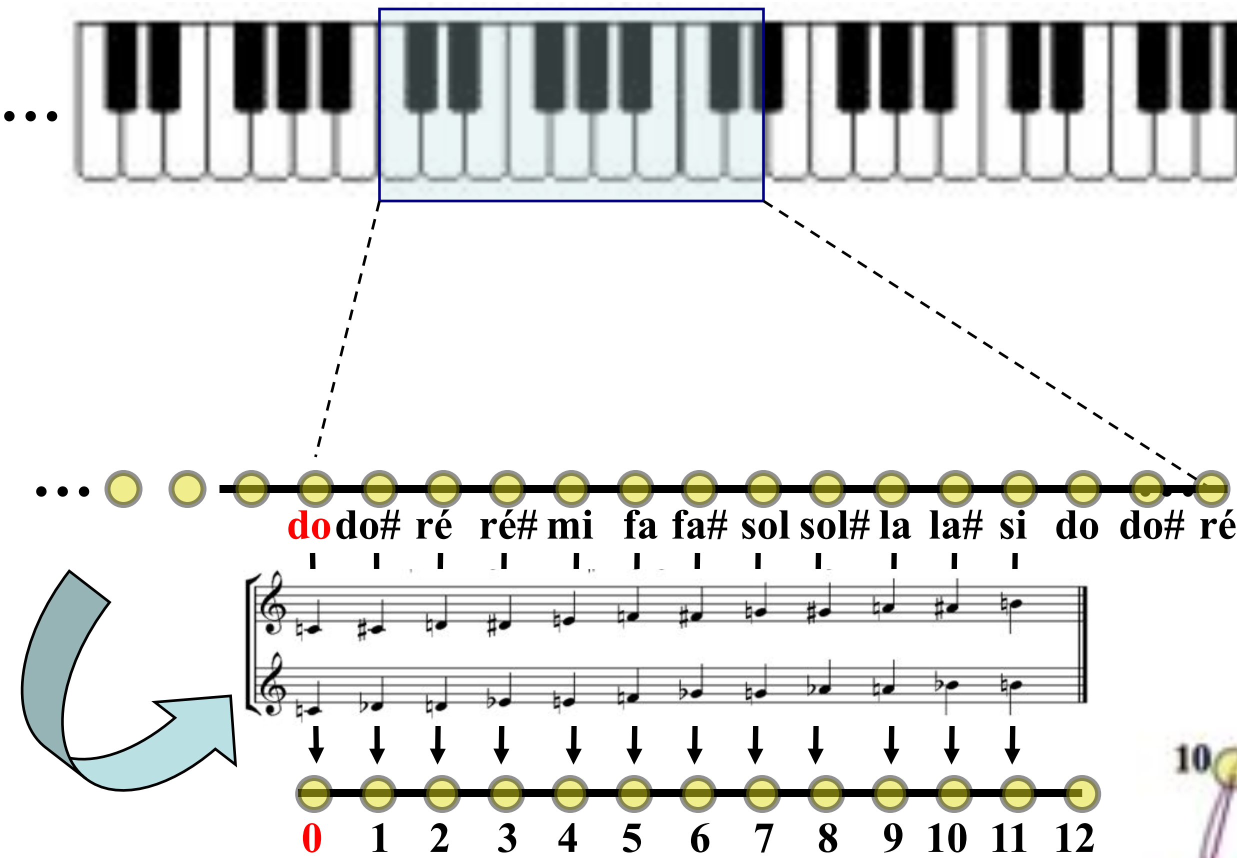


The generators of the cyclic group of order 12 are the transpositions T_1, T_5, T_7 et T_{11} where
$T_k: x \to x+k \mod 12$

$$Z_{12} = \langle T_1 \mid (T_1)^{12} = T_0 \rangle = \langle T_5 \mid (T_5)^{12} = T_0 \rangle = \boldsymbol{\langle T_7 \mid (T_7)^{12} = T_0 \rangle}$$

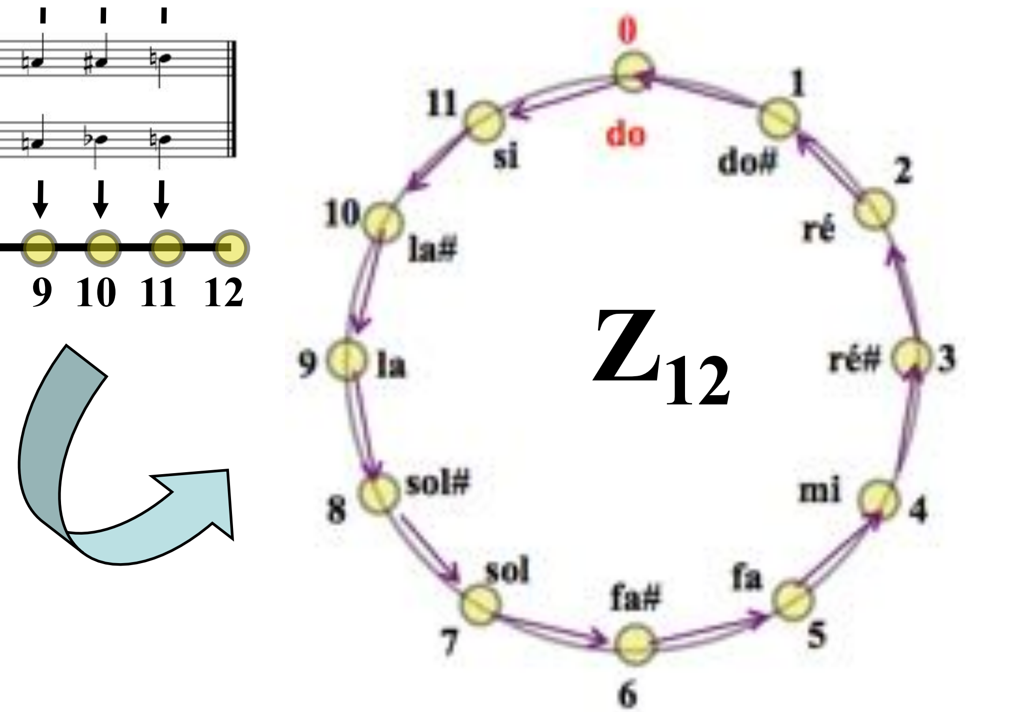


The equal tempered space is a cyclic group



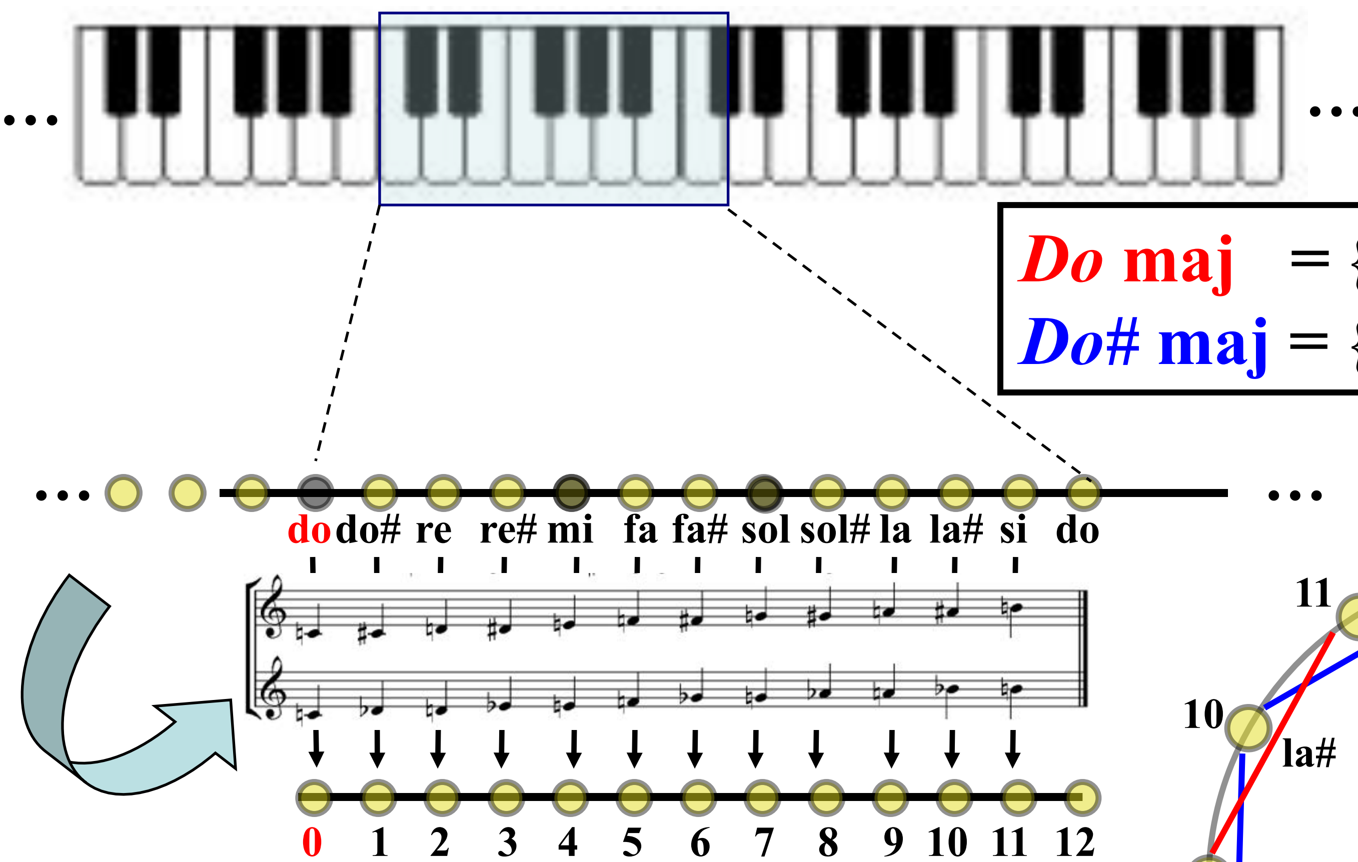
The generators of the cyclic group of order 12 are the transpositions T_1, T_5, T_7 et T_{11} where
$T_k: x \rightarrow x + k \bmod 12$

$$
\begin{aligned}
\mathbf{Z_{12}} &= \langle T_1 \mid (T_1)^{12} = T_0 \rangle = \\
&= \langle T_5 \mid (T_5)^{12} = T_0 \rangle = \\
&= \langle T_7 \mid (T_7)^{12} = T_0 \rangle = \\
&= \langle T_{11} \mid (T_{11})^{12} = T_0 \rangle
\end{aligned}
$$



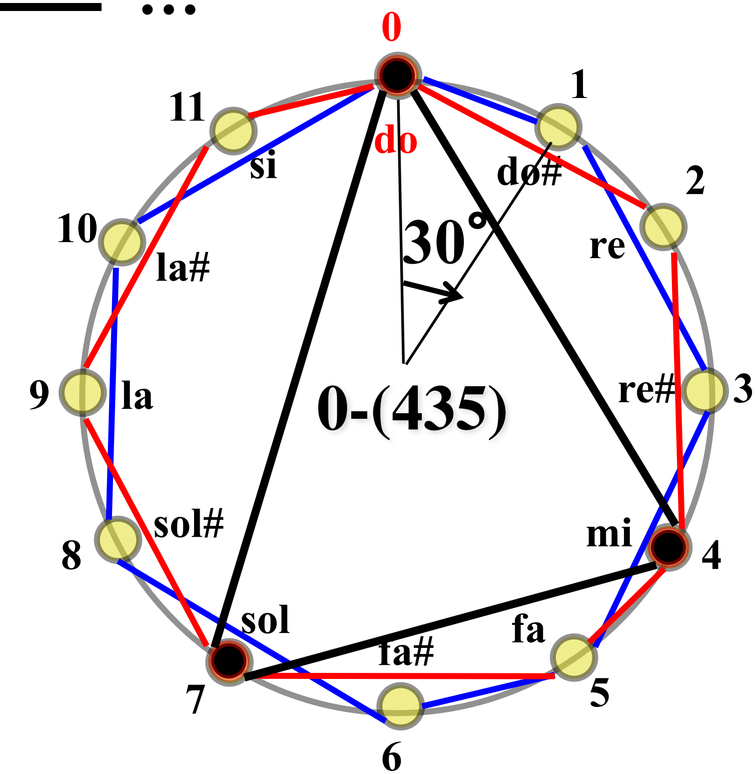
Musical transpositions are additions...

$T_k : x \rightarrow x+k \bmod 12$



Do maj = {0,2,4,5,7,9,11} +1

Do# maj = {1,3,5,6,8,10,0}



...or rotations !

Musical transpositions are additions...

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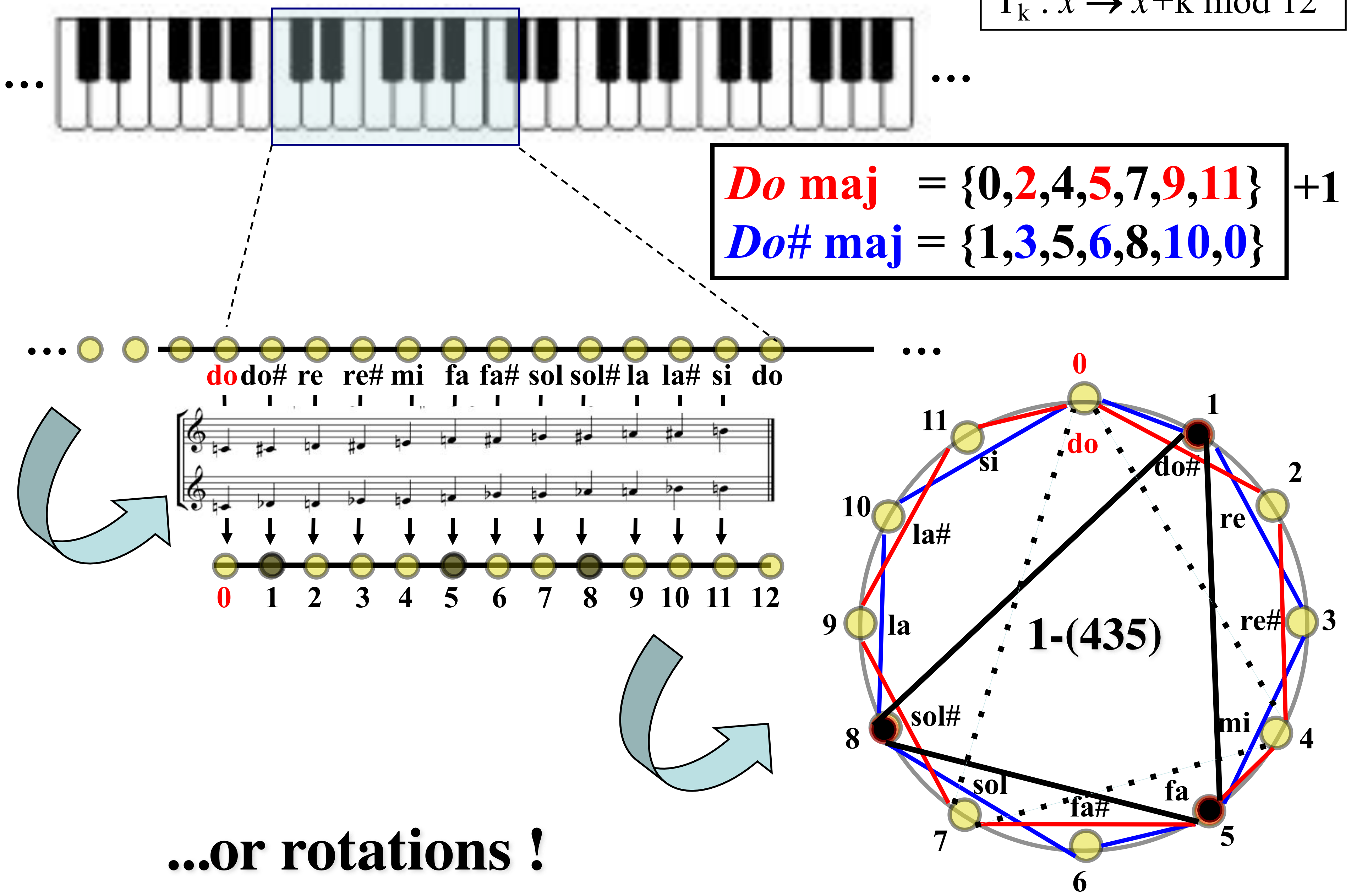
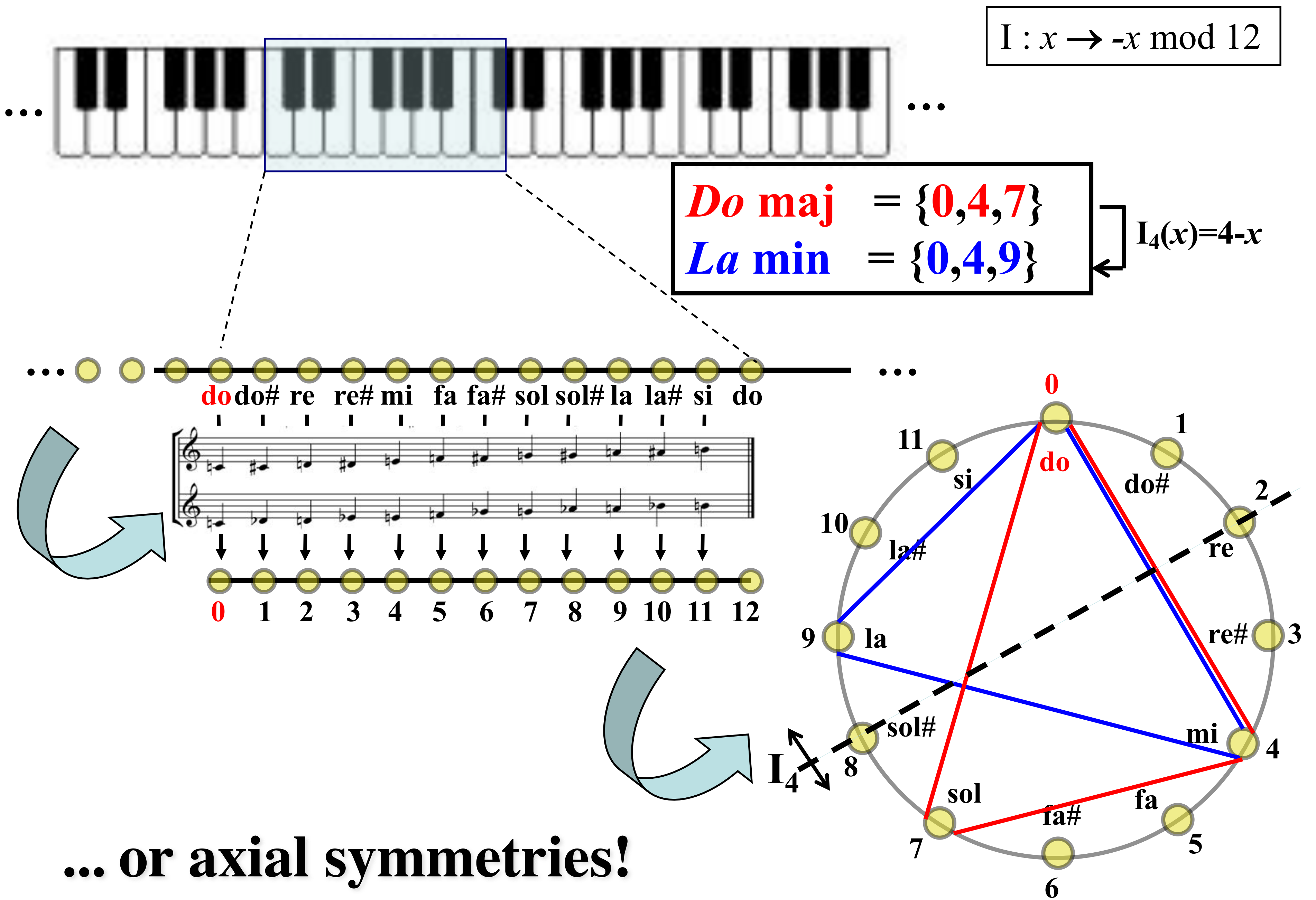


...or rotations !

Musical inversions are differences...



... or axial symmetries!

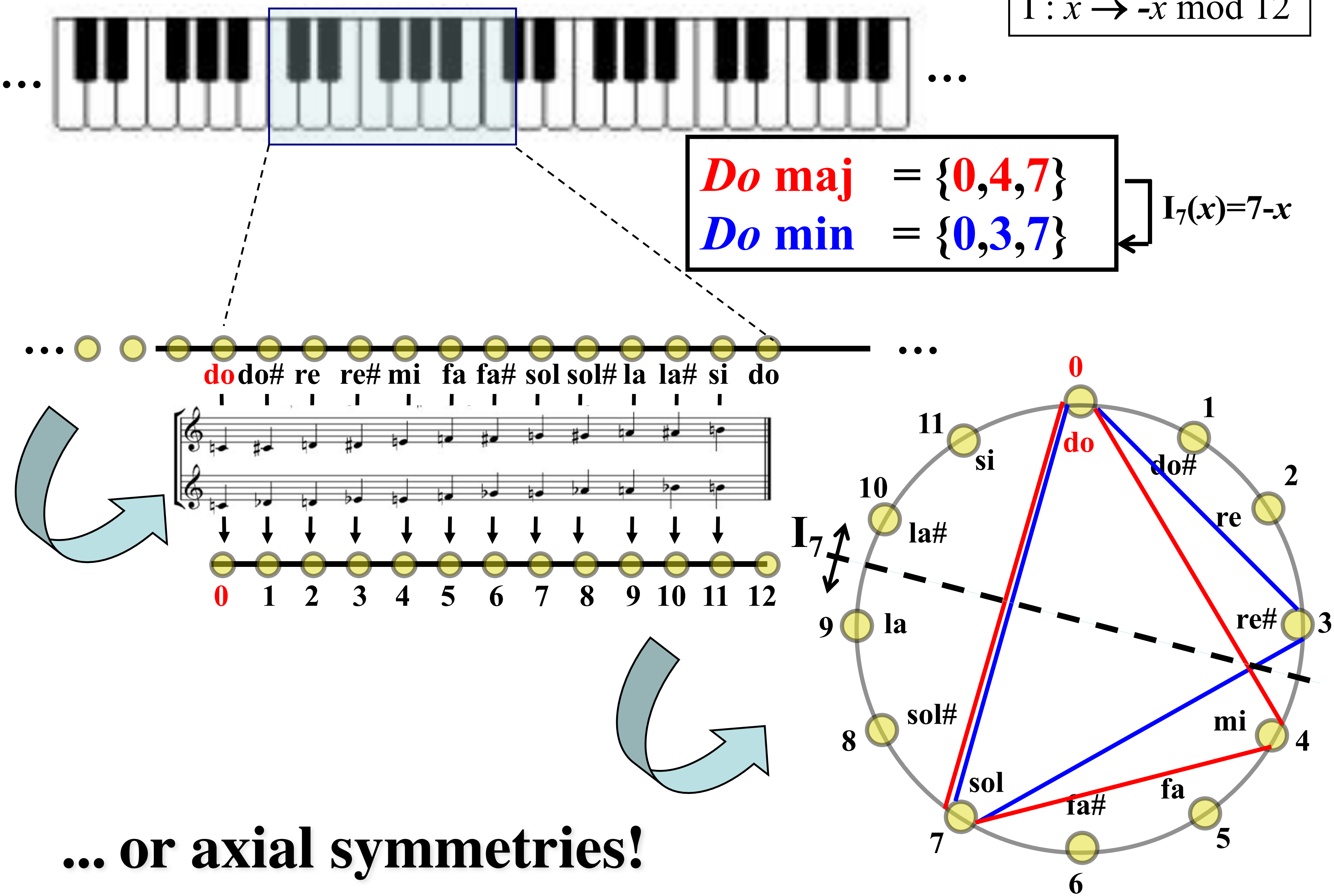
Musical inversions are differences...

$\mathrm{I} : x \rightarrow -x \bmod 12$

Do maj $= \{0,4,7\}$

Do min $= \{0,3,7\}$

$\mathrm{I}_7(x)=7-x$



... or axial symmetries!

Musical inversions are differences...

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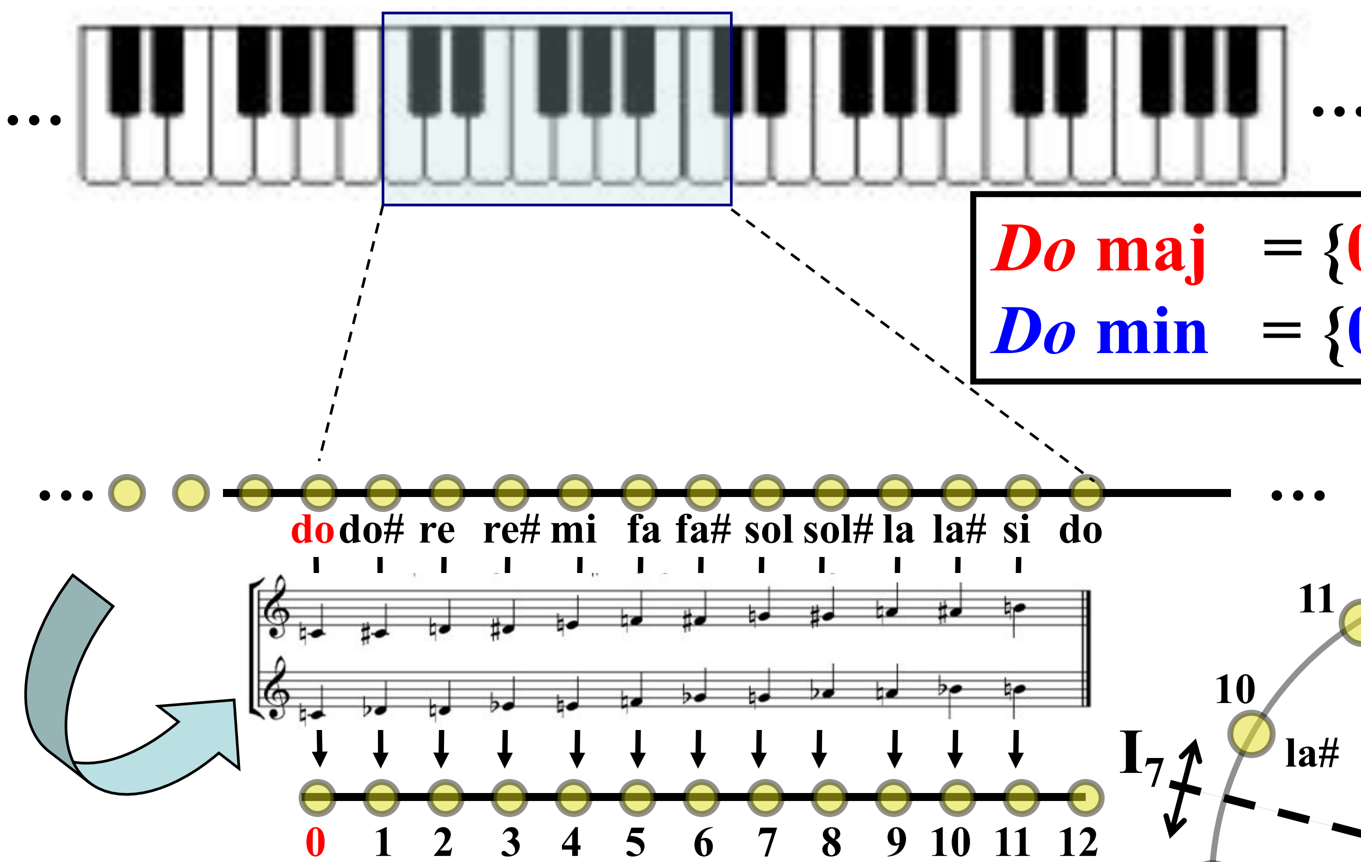

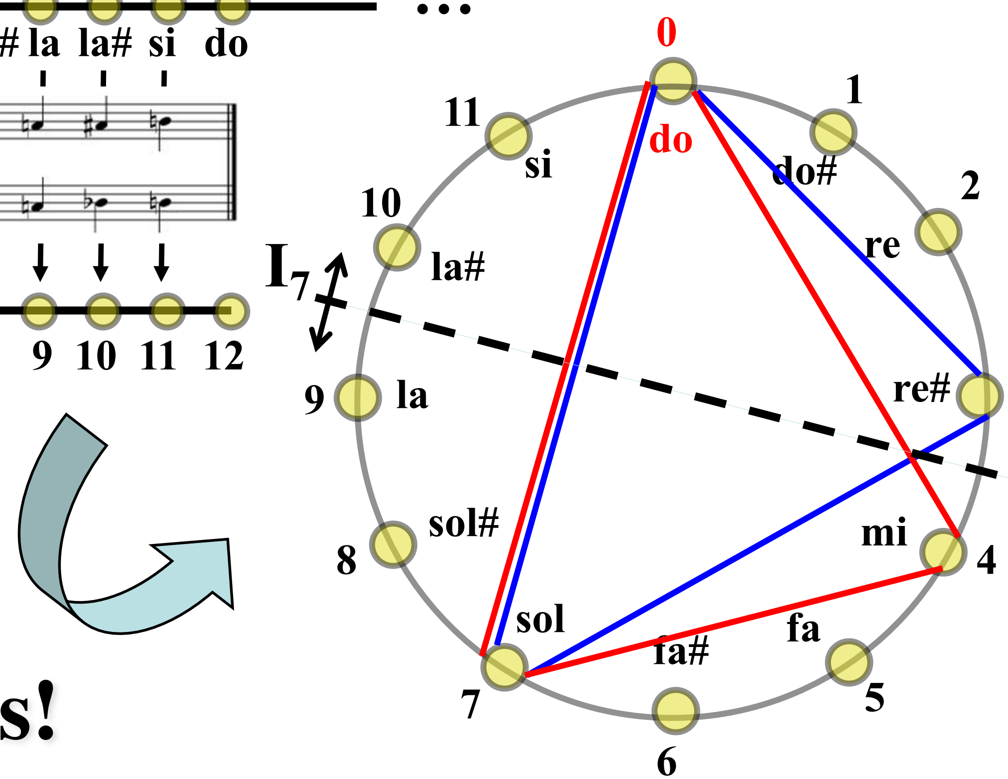

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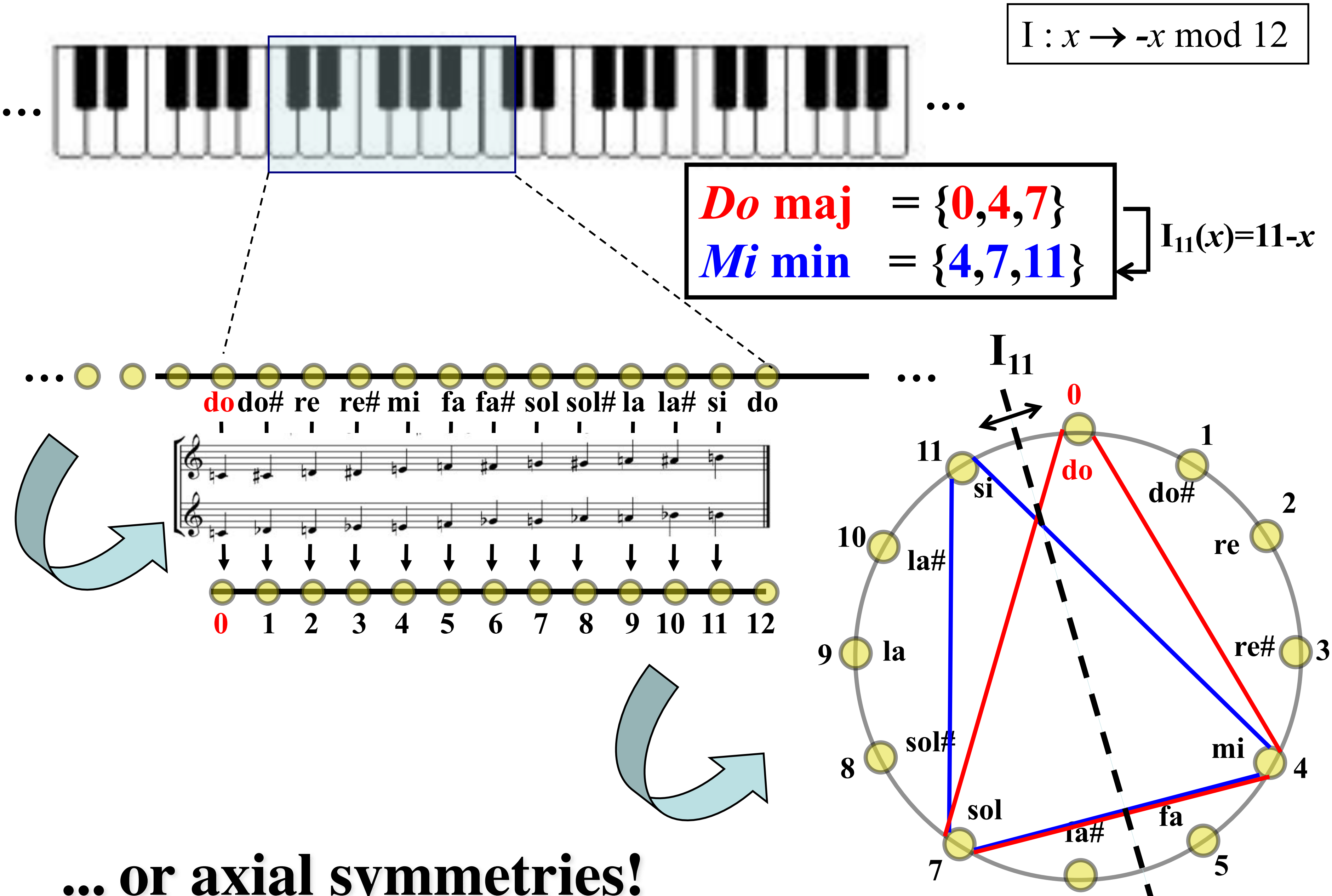
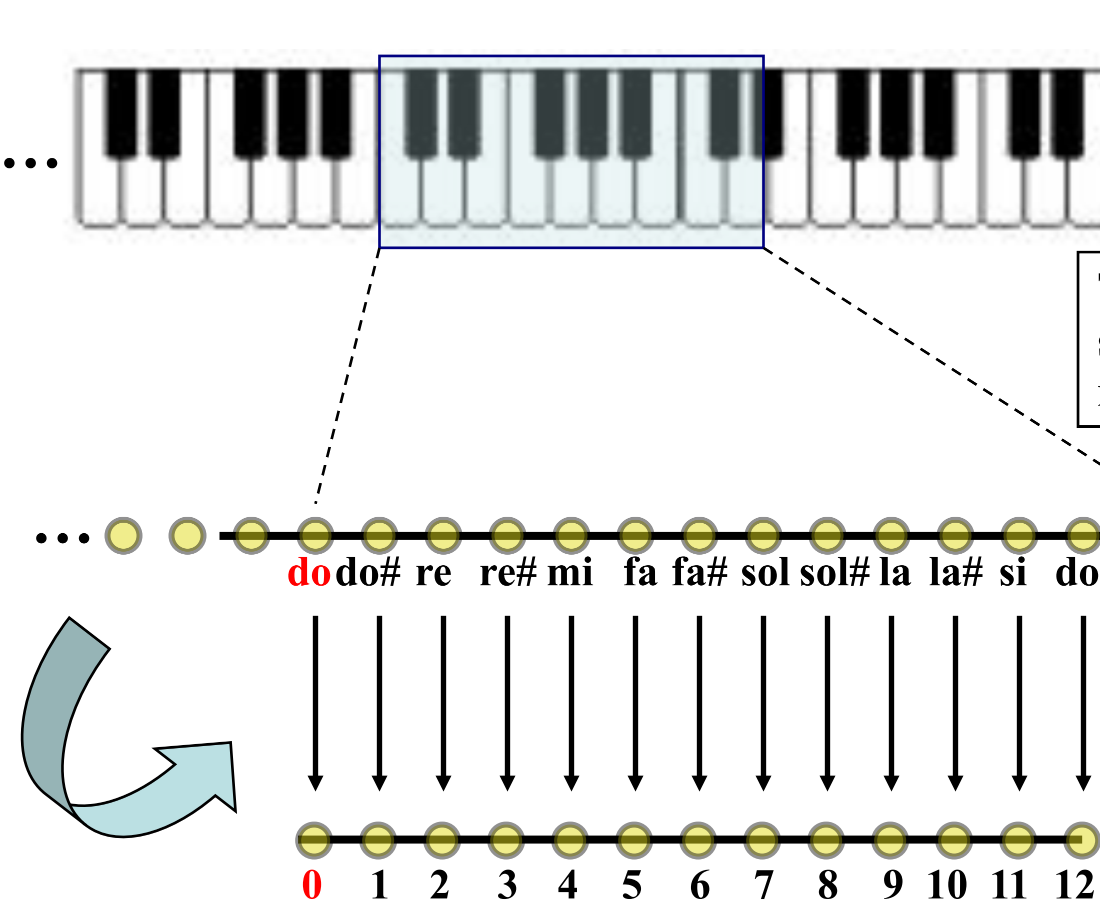
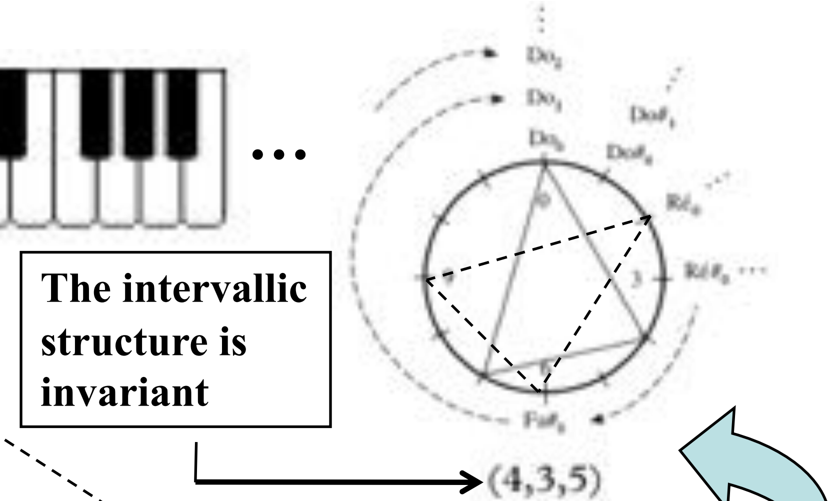
Musical inversions are differences...

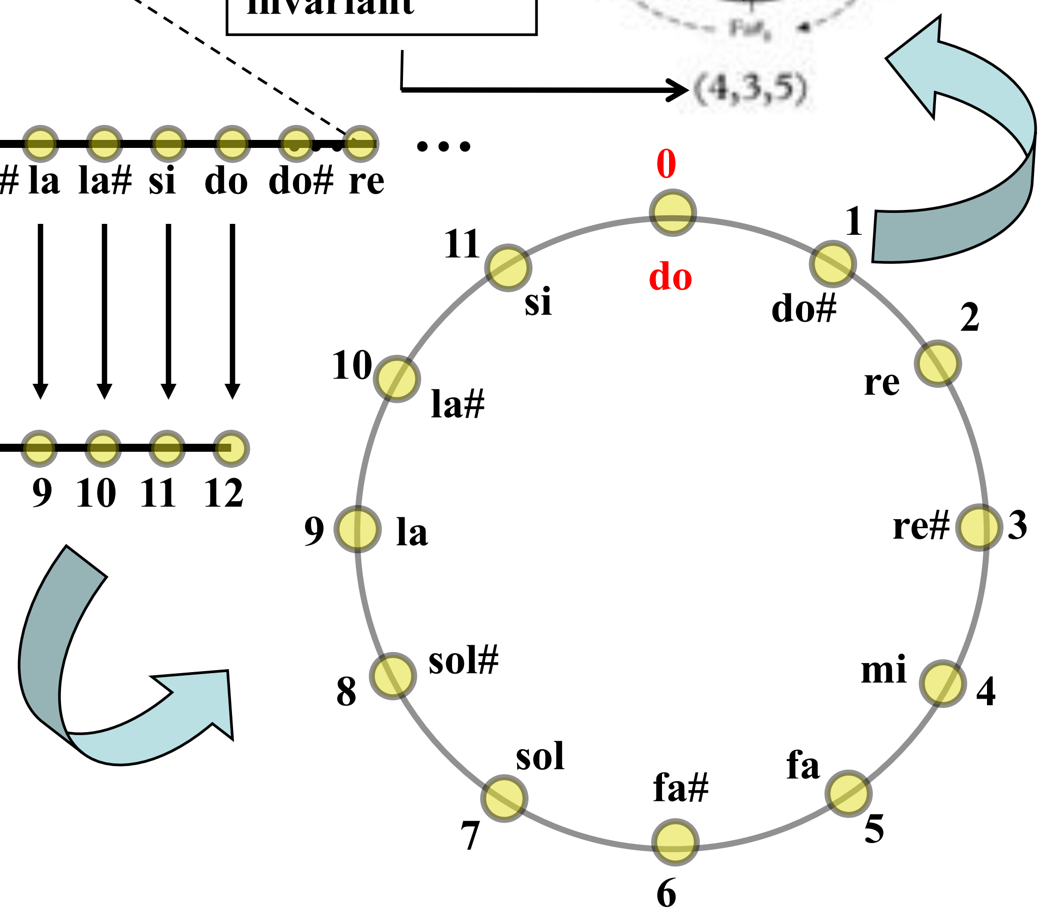


... or axial symmetries!

Circular representation and intervallic structure





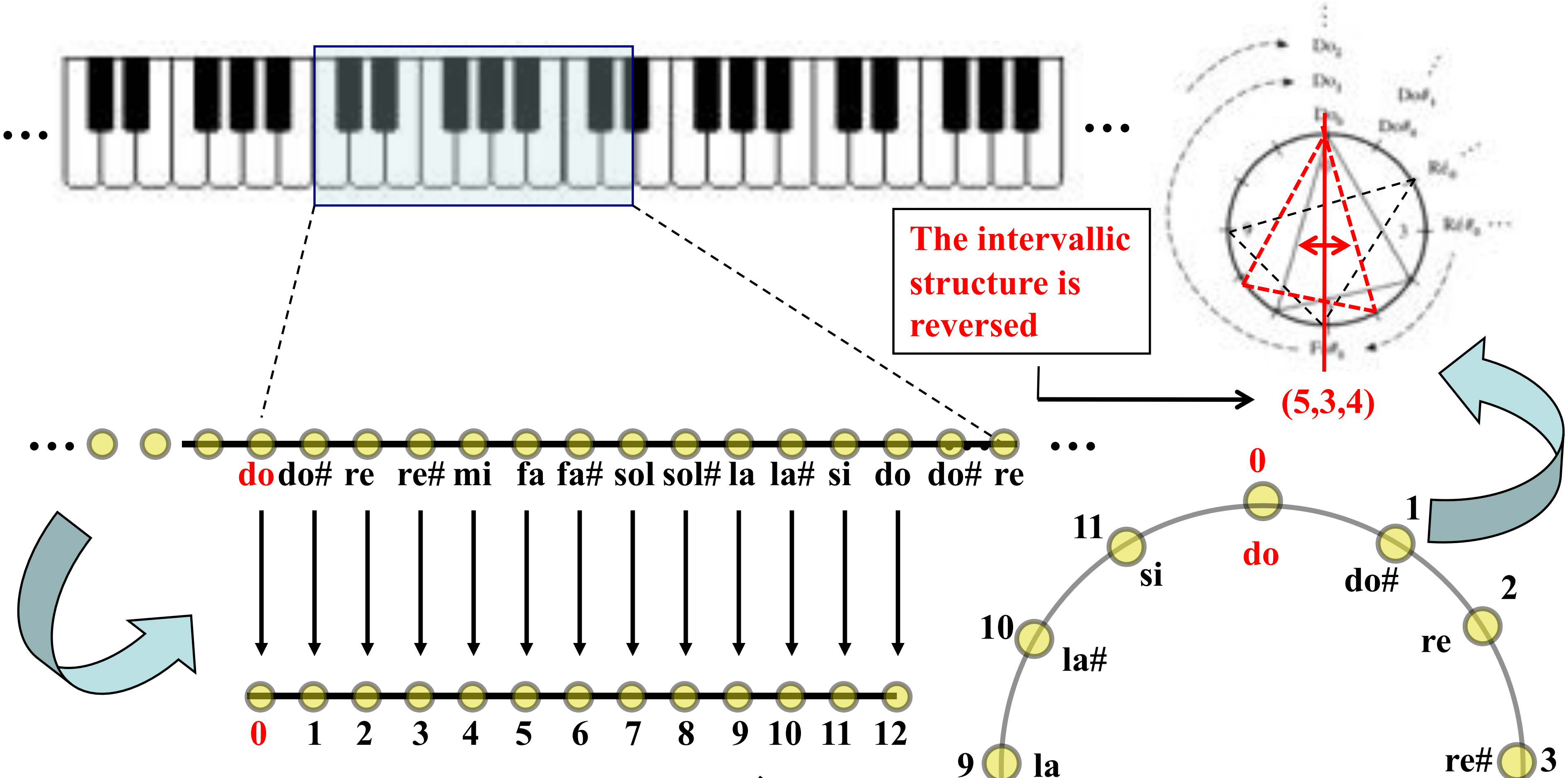


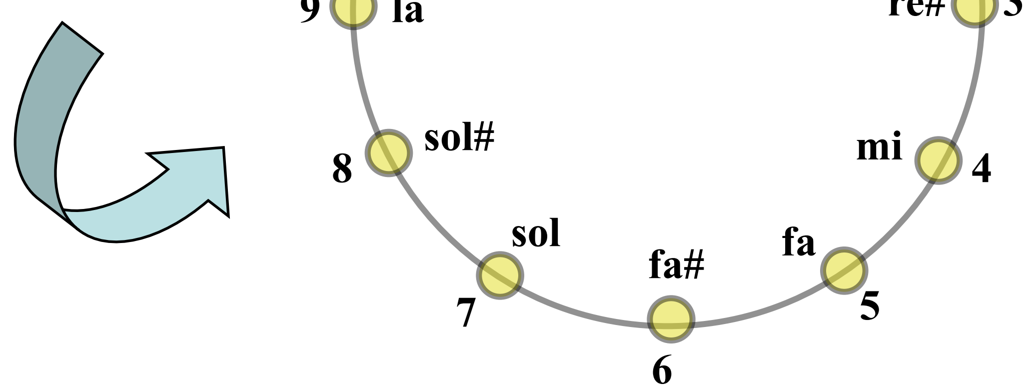
The two basic musical applications

$T_k : x \rightarrow x+k \bmod 12$ (transposition)

$I : x \rightarrow -x \bmod 12$ (inversion)

Circular representation and intervallic structure



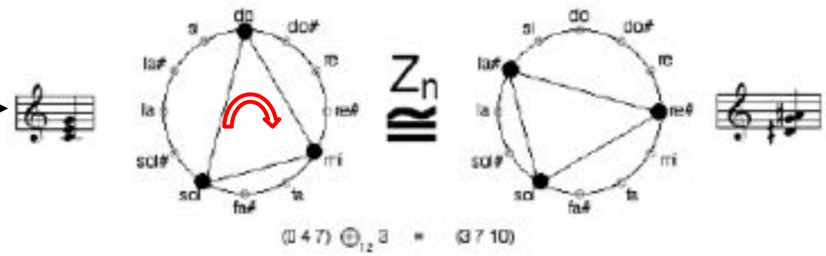


The two basic musical applications

$T_k : x \rightarrow x + k \mod 12$ (transposition)

$I : x \rightarrow -x \mod 12$ (inversion)

Equivalence classes of musical structures
(up to a group action)

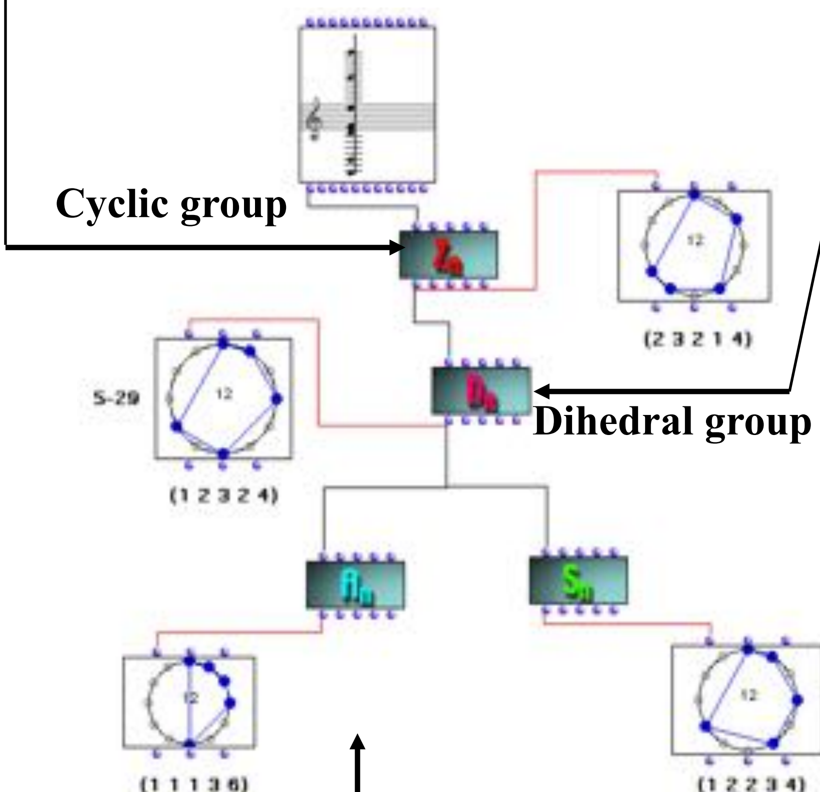


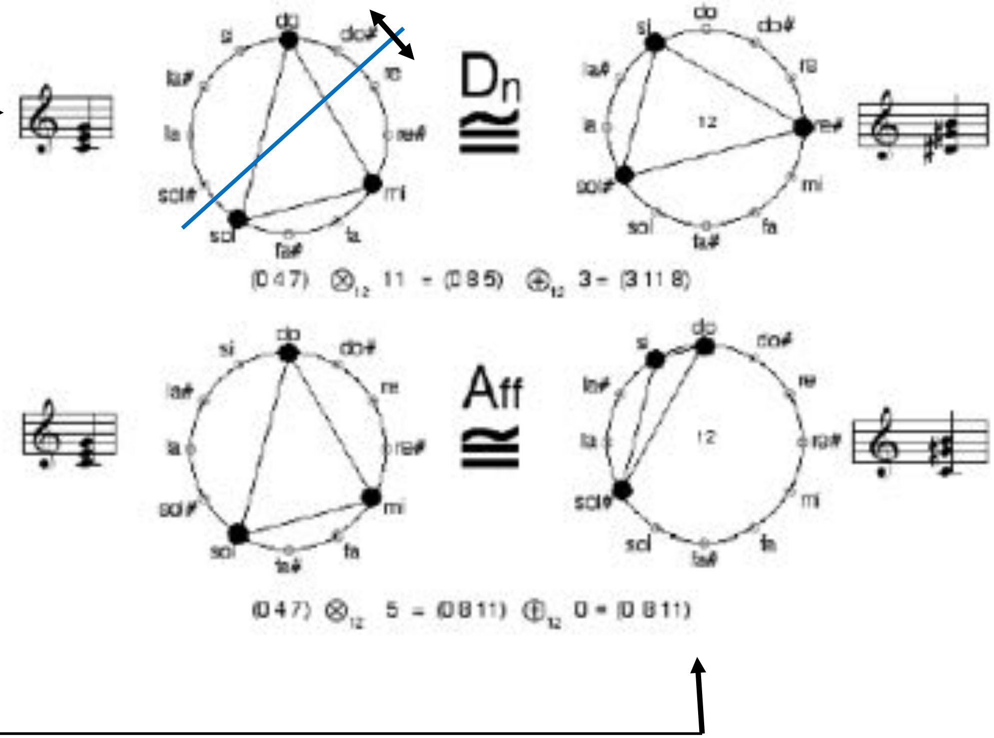
$\mathbf{Z_{12}} = \langle T_k \mid (T_k)^{12} = T_0 \rangle$ where $T_k(x)=x+1$

$\mathbf{D_{12}} = \langle T_k , I \mid (T_k)^{12} = I^2 = T_0 , ITI=I(IT)^{-1} \rangle$

where $I(x)=-x$

$\mathbf{Aff} = \{ f \mid f(x)=ax+b,\ a\in(\mathbf{Z_{12}})^*,\ b\in\mathbf{Z_{12}} \}$





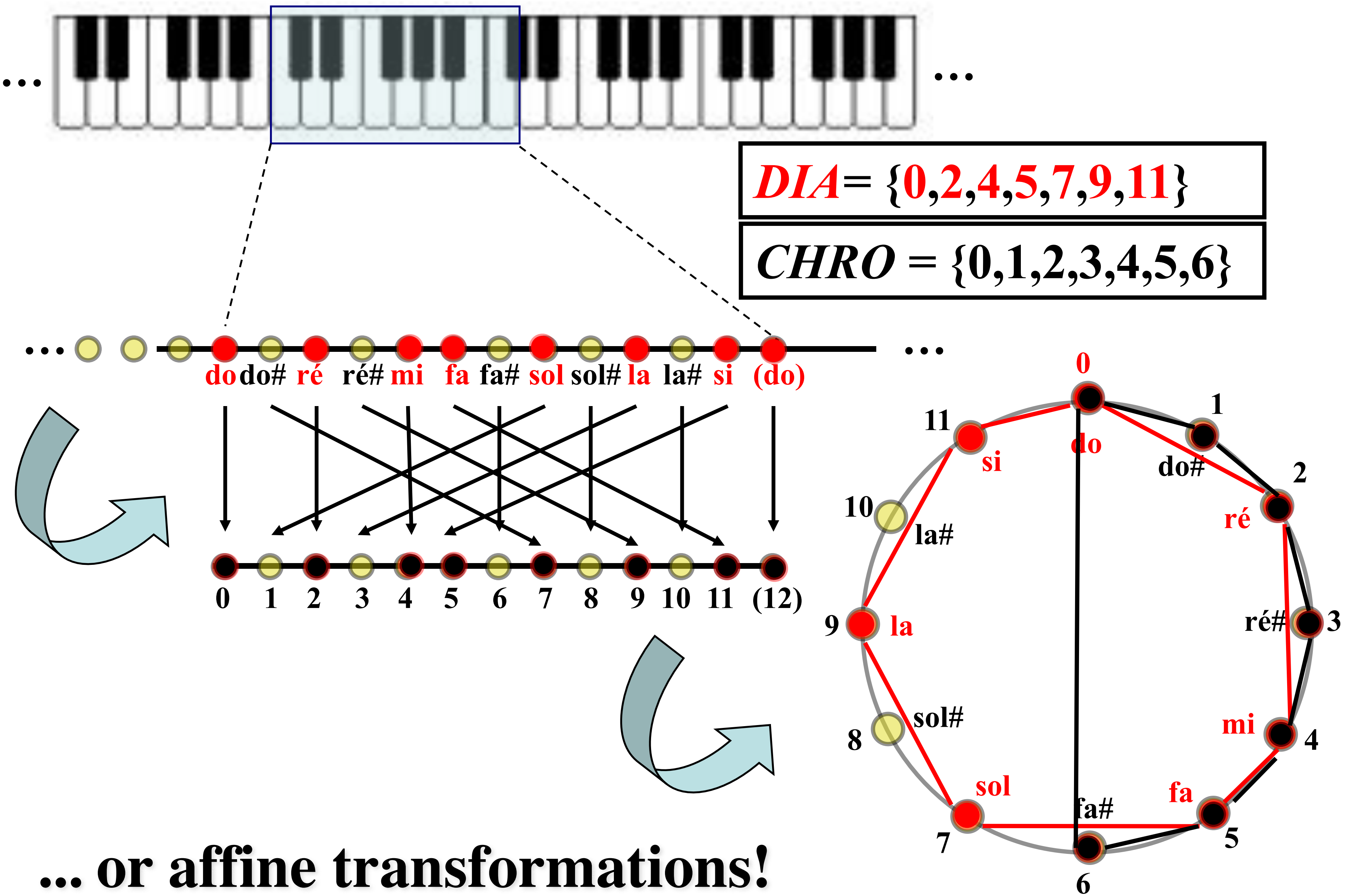
Affine group

Paradigmatic architecture

Augmentations are multiplications...

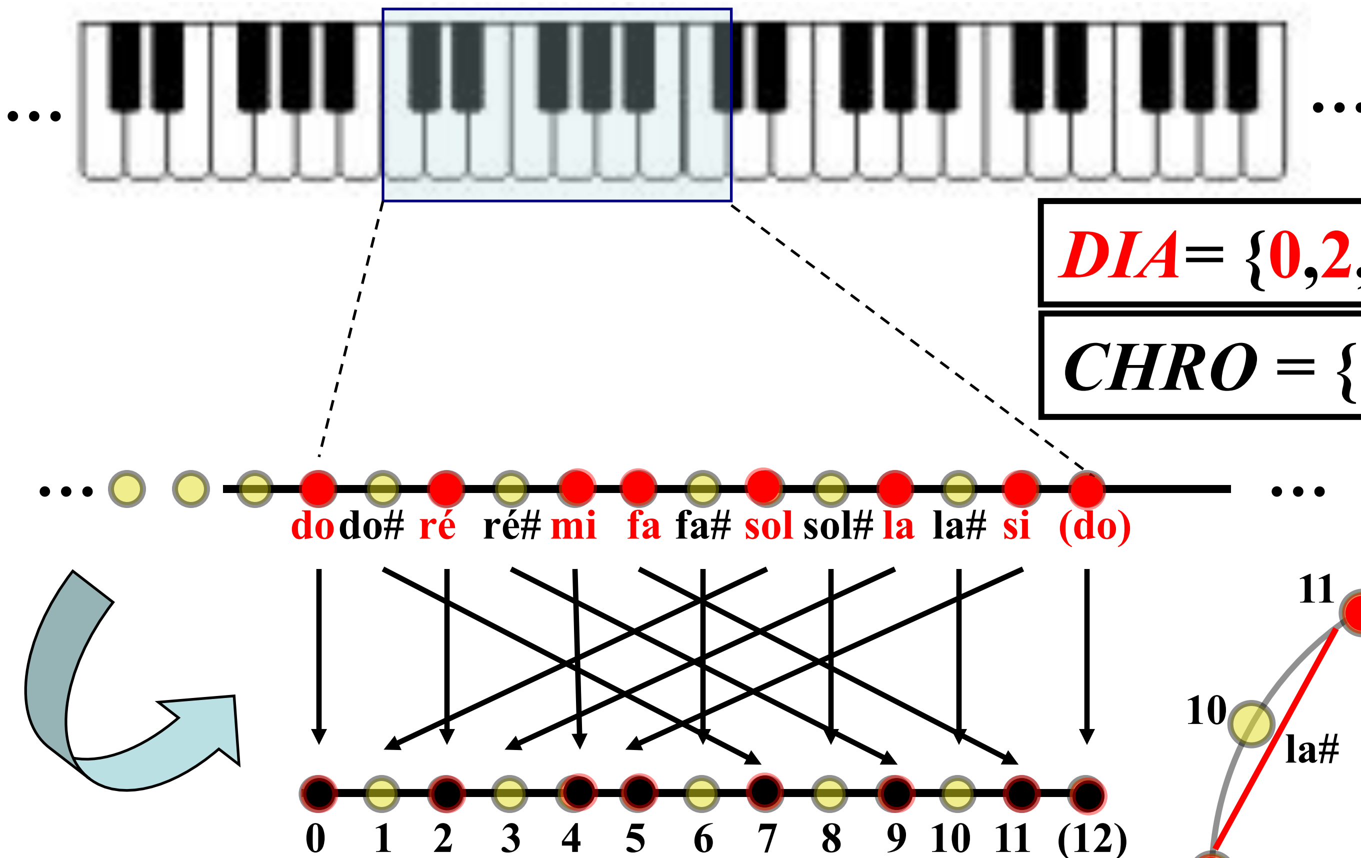
$DIA = \{0,2,4,5,7,9,11\}$

$CHRO = \{0,1,2,3,4,5,6\}$



... or affine transformations!

Affine transformations and DIA/CHRO duality



$DIA = \{0,2,4,5,7,9,11\}$

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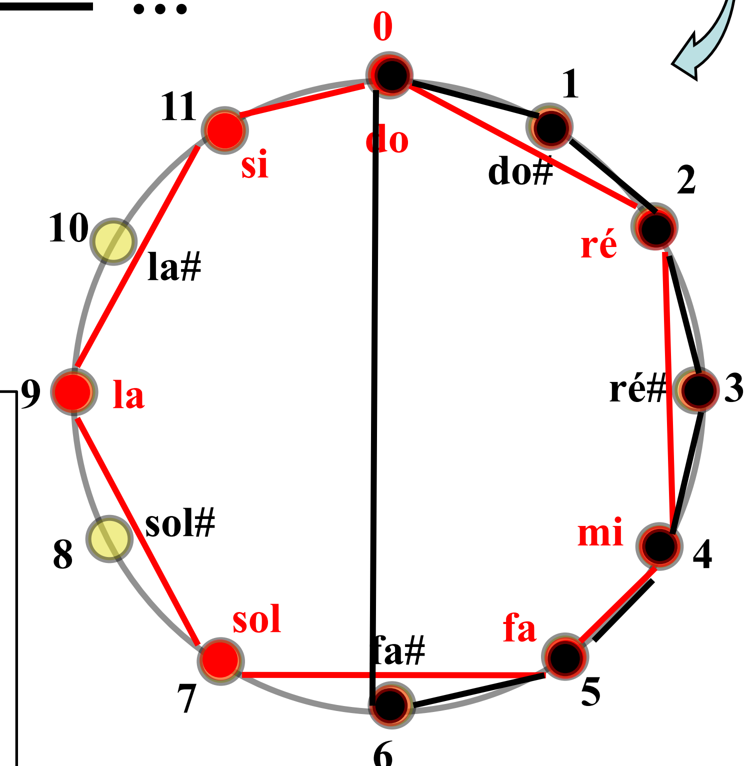
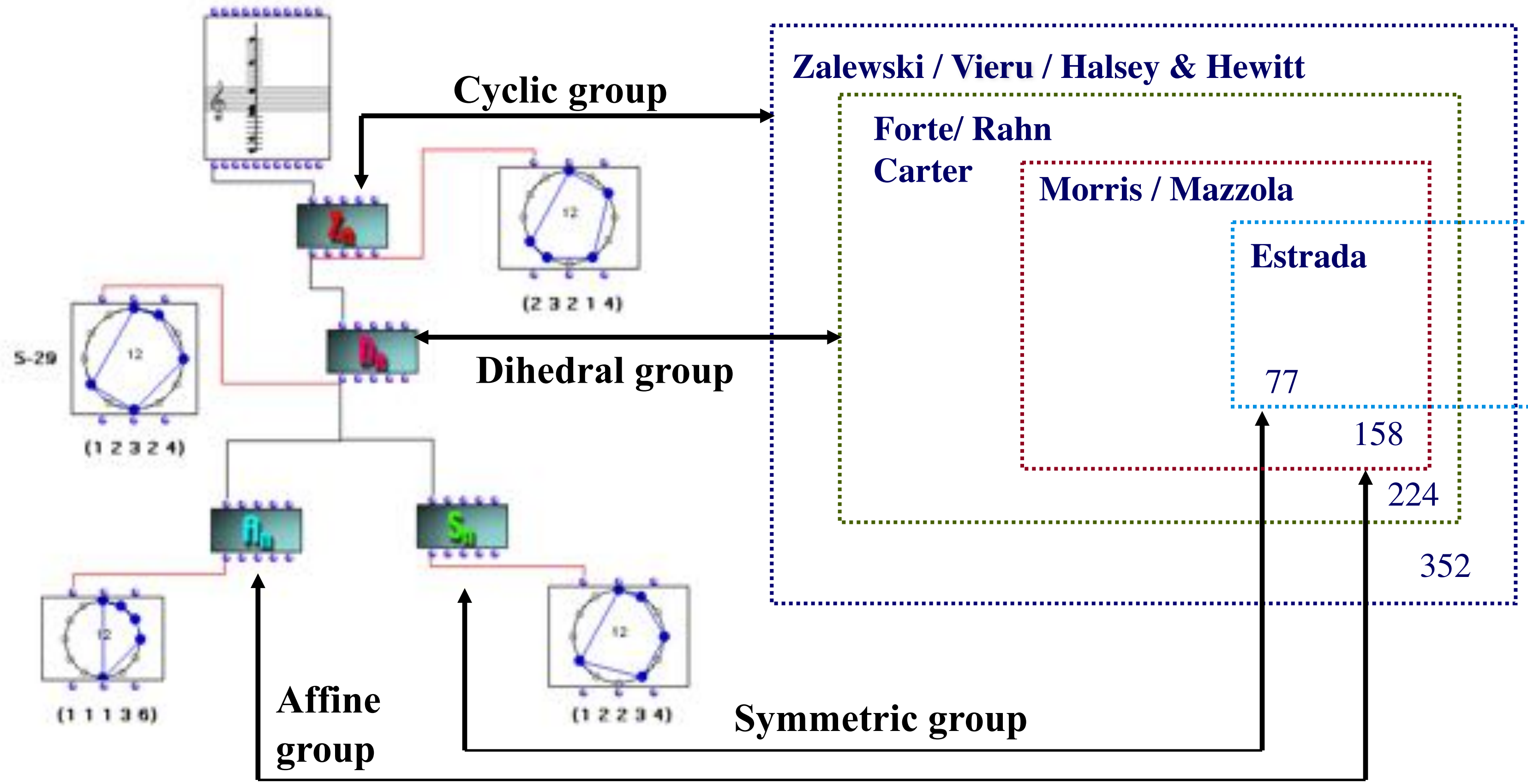


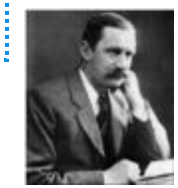
« Le **diatonisme** et le **chromatisme** ne peuvent pas être envisagés en termes de simplicité ou de complexité, comme on le pensait jadis. Il s'agit plutôt d'une question **d'unité des contraires** dans le groupe **Z/12Z** »

(A. Vieru, « The Musical Signification of Multiplication by 7. Diatonicity and Chromaticity », *Muzica,* 1995)

Group actions and the classification of musical structures



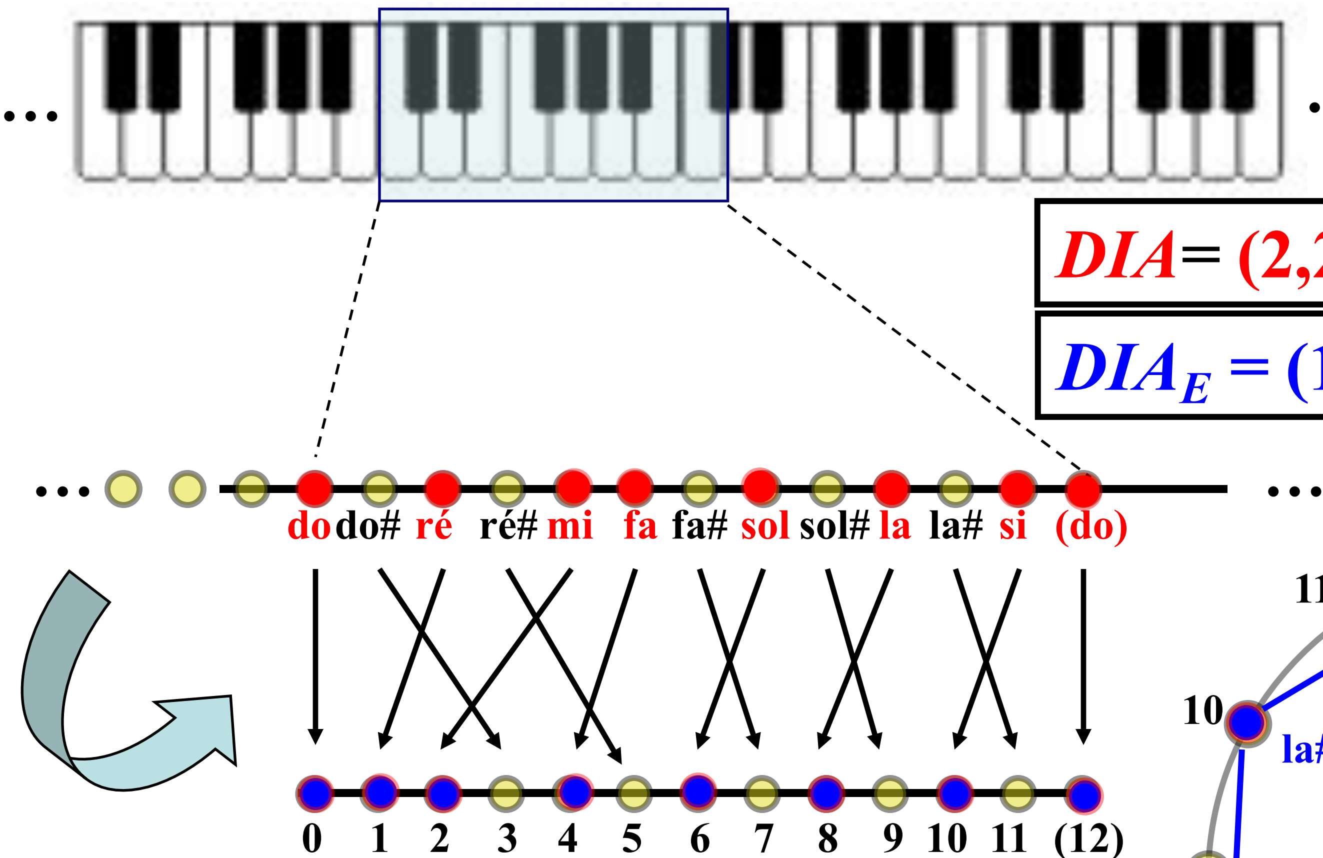

F. Klein


W. Burnside


G. Polya

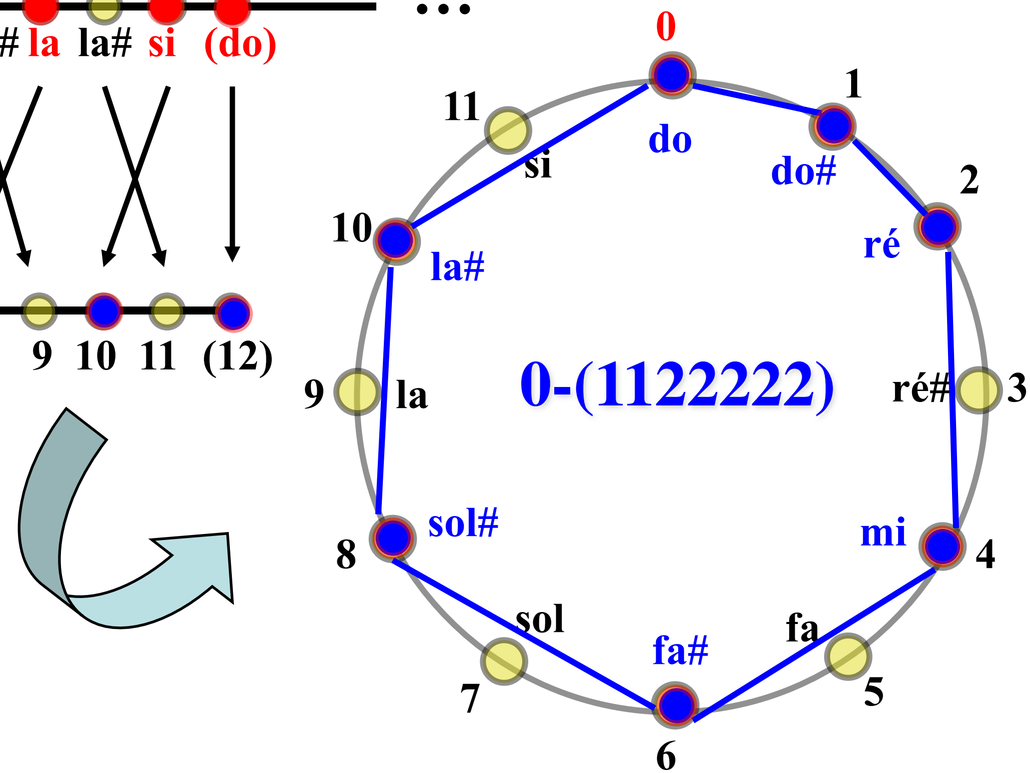
	1	2	3	4	5	6	7	8	9	10	11	12
Z_n	1	6	19	43	66	80	66	43	19	6	1	1
D_n	1	6	12	29	38	50	38	29	12	6	1	1
A_n	1	5	9	21	25	34	25	21	9	5	1	1
S_n	***1***	***6***	***12***	***15***	***13***	***11***	***7***	***5***	***3***	***2***	***1***	***1***

Classifying chords up to permutations of intervals



$DIA = (2,2,1,2,2,2,1)$

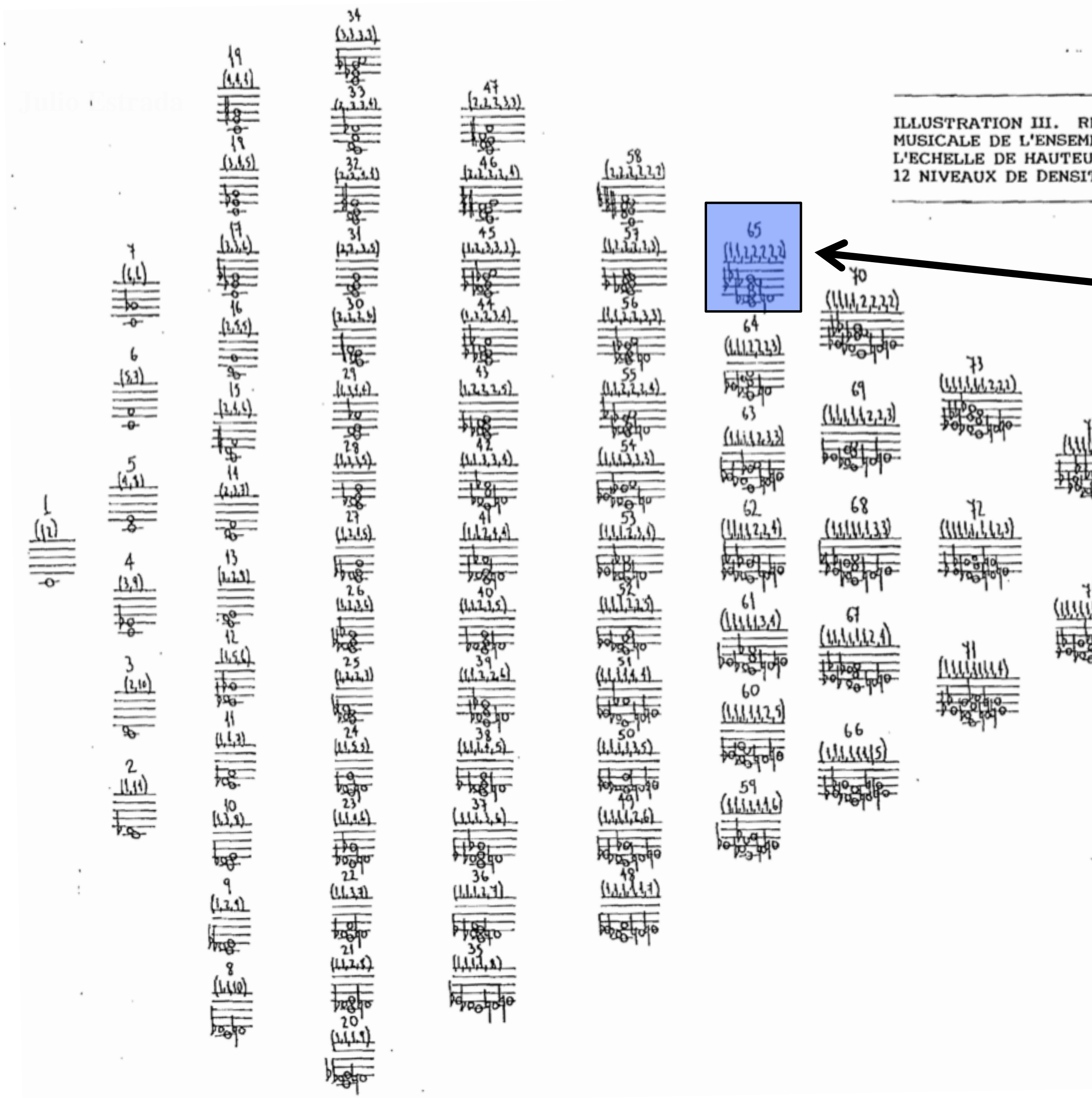
$DIA_E = (1,1,2,2,2,2,2)$



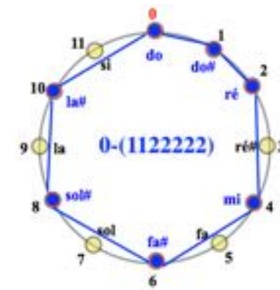
Julio Estrada, *Théorie de la composition : discontinuum – continuum,* université de Strasbourg II, 1994

The permutohedron as a combinatorial space

Julio Estrada, *Théorie de la composition : discontinuum – continuum*, université de Strasbourg II, 1994



DIA_E = (1,1,2,2,2,2,2)




THEORIE DE LA COMPOSITION :

DISCONTINUUM - CONTINUUM

Julio ESTRADA

Thèse en Musicologie

Nouveau Doctorat

Département de Musicologie

Université de Strasbourg II

Sciences Humaines

Directeur de thèse :
François-Bernard Mâche

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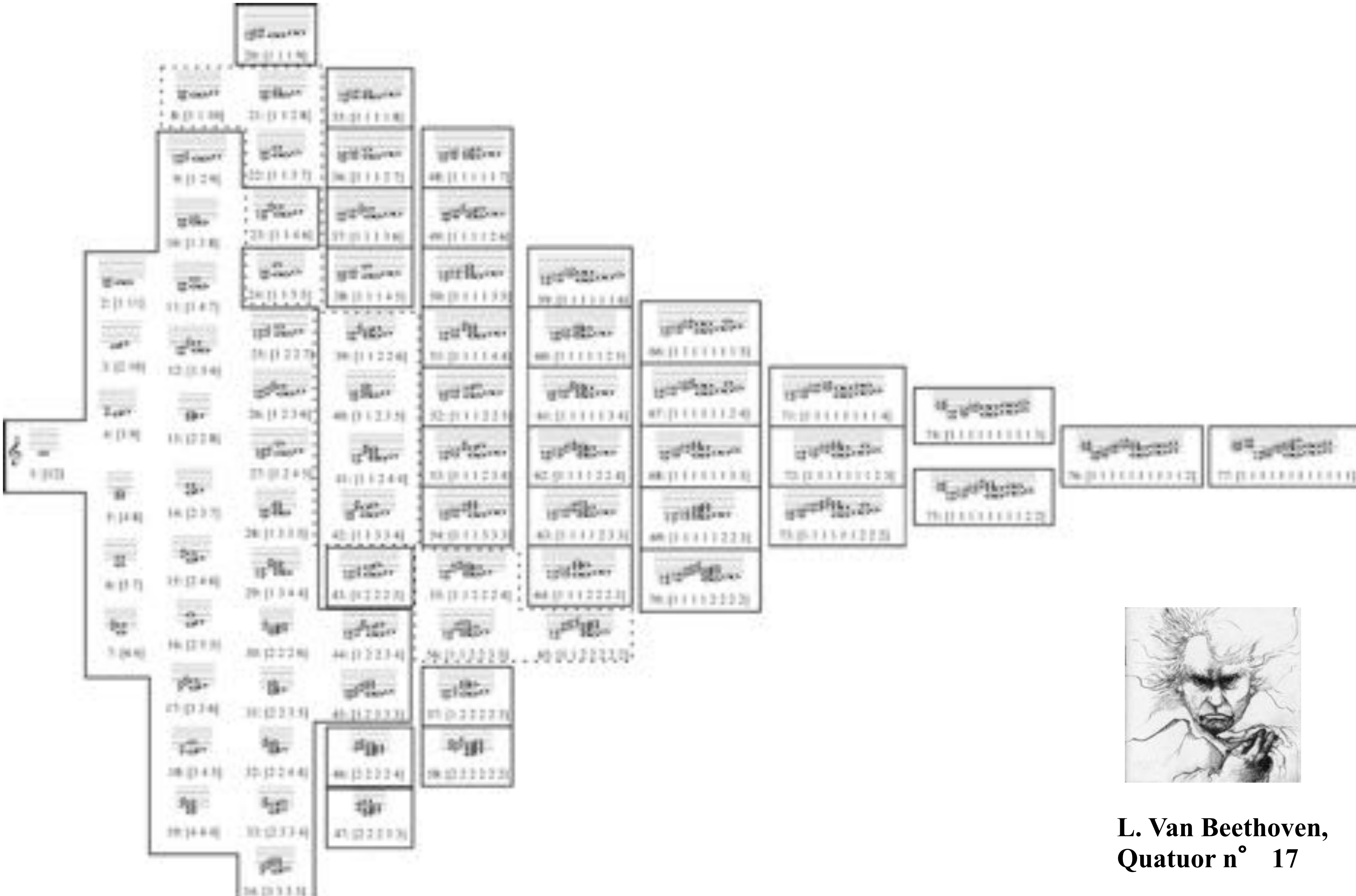
M. Daniel Charles, Université de Nice

J. Estrada

The permutohedron as a musical conceptual space



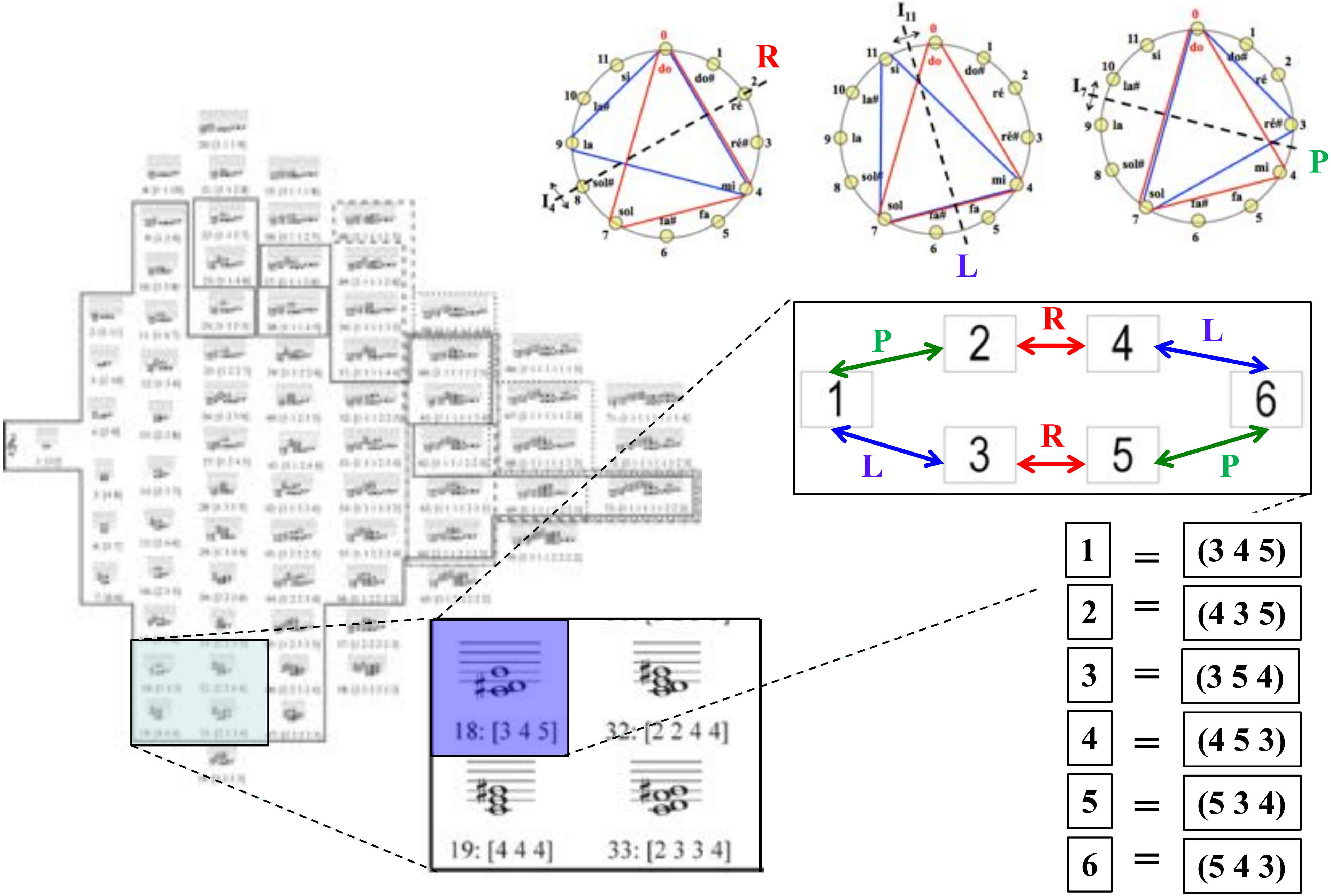
L. Van Beethoven, Quatuor n° 17

The permutohedron as a musical conceptual space

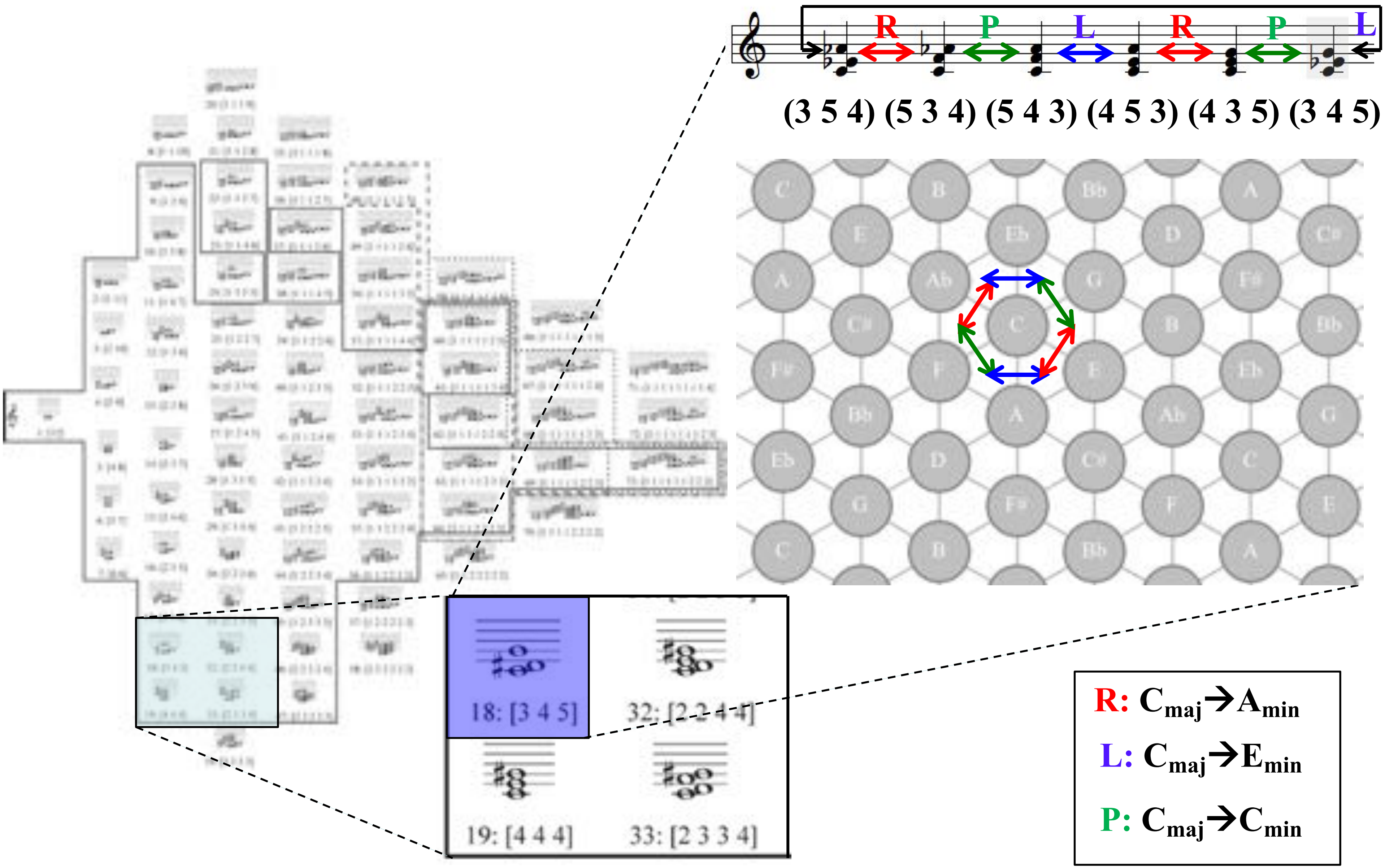
B. Bartok, Quartet n° 4
(3d movement)

A. Schoenberg,
***Six pieces* op. 19**

Permutohedron and *Tonnetz*: a structural inclusion



Permutohedron and *Tonnetz*: a structural inclusion



Permutohedron and *Tonnetz*: a structural inclusion