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Information Leakage in a Music Score

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When I was invited to contribute to a Festschrift in honor of Catuscia Palamidessi, I immediately thought I should not miss the opportunity to express my friendly feelings and admiration for the research career of a good friend of 30 years.

Initially, we had some common research axes on Logic Programming and Concurrent Constraint Programming. The GULP conference on these topics in Italy was a high place where Catuscia had no equal to defend, between Pisa and Florence, what should be the true Italian pronunciation, but with too subtle arguments for a foreigner. In 1990, the ICLP conference in Jerusalem and Eilat was a memorable mark of Catuscia's passion for Concurrent Logic Programming. In 2000, our small CSE Penn State-Inria workshop on "Concurrency and Logic" was premonitory of a new life for Catuscia at Inria. In the last decade however, our research interests evolved in different directions, respectively on quantitative information flows and quantitative biology.

When reading the recent papers of Catuscia on information leakage in information flows, in the quest of finding something to write related to those topics, a music unexpectedly came to my mind, with two concurrent voices playing obsessively on some jazzy rhythm, responding each other, and producing some bits of information about a secret message subject to interpretation, as always in music.

It is my pleasure to dedicate that little piece of music, called "*Concur in C*", to Catuscia for her 60th birthday. The music score is given below¹.

But could we try to apply Catuscia's theory on information leakage in information flows to the notes of each voice, in the hope of revealing something more on the meaning of this mysterious musical message remained enigmatic to the composer?

In information flow theory, a *channel*, or a *voice* in our musical interpretation, is a triple (X, Y, C) , where X and Y are finite sets (of secret input values and produced output music notes) and the channel matrix C is an $|X| \times |Y|$ matrix giving the probability of getting output y when the input is x . Given a prior distribution π on X , the joint distribution $p(x, y) = \pi[x]C[x, y]$ on random variables $X \times Y$ is the (unique) joint distribution that gives marginal probabilities $p(x) = \sum_y p(x, y) = \pi[x]$, conditional probabilities $p(y|x) = p(x, y)/p(x) = C[x, y]$ (if $p(x)$ is nonzero), and similarly $p(y)$ and $p(x|y)$.

The marginal distribution of the music notes in a voice are given by the frequencies of the notes in that voice. In *Concur in C*, the upper and lower voices happen to play the same number of notes, 186, with slightly different

¹ "*Concur in C*" can be heard with several orchestrations (piano, flute-saxophone, flute-organ-bass, big band) on <http://lifeware.inria.fr/~fages/music/>

distributions and slightly higher Shannon's entropy ($-\sum_{i=1}^{186} p_i(y) \cdot \log_2(p_i(y))$), i.e. more information, in the upper voice:

number of occurrences	C	C# Db	D	D# Eb	E	F	F# Gb	G	G# Ab	A	A# Bb	B	total
upper voice	32	0	0	54	2	14	20	40	0	0	22	2	186
$p^u(y)$	0.17	0	0	0.29	0.01	0.07	0.11	0.22	0	0	0.12	0.01	entropy 2.56
lower voice	41	0	0	36	0	22	27	39	0	0	21	0	186
$p^l(y)$	0.22	0	0	0.19	0	0.12	0.15	0.21	0	0	0.11	0	entropy 2.53

In music, it is expected that the upper voice contains more information than the lower voice usually dedicated to accompaniment. But here, the two voices play similar melodies in counterpoint which results in similar entropy values for both voices. It would be interesting to test this approach on more elaborate scores.

Thank you Catuscia for having once again inspired me, in an unexpected fashion, this self-surprising gift with curious questions about the quantification of information in music.

There has always been something magic in you.

Happy 60th Birthday Catuscia!

Acknowledgments: special thanks go to Hubert Garavel for having improved the layout of my music score, and for his tolerance regarding my parallel fifths.

Concur in C

To Catuscia Palamidessi for her 60th birthday

F. Fages

♩ = 110

Piano

Measures 1-2 of the piano score. The key signature is C major (one flat). The time signature is 4/4. The melody in the right hand consists of eighth notes: C4, D4, E4, F4, G4, A4, B4, C5, followed by a repeat of the first seven notes. The left hand has whole rests.

Measures 3-4. The melody continues with eighth notes: D5, C5, B4, A4, G4, F4, E4, D4. The left hand has eighth notes: C4, D4, E4, F4, G4, A4, B4, C5.

Measures 5-7. Measure 5: Right hand has eighth notes C4, D4, E4, F4, G4, A4, B4, C5; left hand has eighth notes C4, D4, E4, F4, G4, A4, B4, C5. Measure 6: Right hand has eighth notes C4, D4, E4, F4, G4, A4, B4, C5; left hand has eighth notes C4, D4, E4, F4, G4, A4, B4, C5. Measure 7: Right hand has eighth notes C4, D4, E4, F4, G4, A4, B4, C5; left hand has eighth notes C4, D4, E4, F4, G4, A4, B4, C5.

Measures 8-10. Measure 8: Right hand has eighth notes C4, D4, E4, F4, G4, A4, B4, C5; left hand has eighth notes C4, D4, E4, F4, G4, A4, B4, C5. Measure 9: Right hand has eighth notes C4, D4, E4, F4, G4, A4, B4, C5; left hand has eighth notes C4, D4, E4, F4, G4, A4, B4, C5. Measure 10: Right hand has eighth notes C4, D4, E4, F4, G4, A4, B4, C5; left hand has eighth notes C4, D4, E4, F4, G4, A4, B4, C5.

Measures 11-12. Measure 11: Right hand has eighth notes C4, D4, E4, F4, G4, A4, B4, C5; left hand has eighth notes C4, D4, E4, F4, G4, A4, B4, C5. Measure 12: Right hand has eighth notes C4, D4, E4, F4, G4, A4, B4, C5; left hand has eighth notes C4, D4, E4, F4, G4, A4, B4, C5.

13

Measures 13 and 14 of a musical score in B-flat major (two flats). The treble clef contains eighth-note chords and single notes, while the bass clef features a continuous eighth-note accompaniment. Measure 13 ends with a repeat sign.

15

Measures 15, 16, and 17. Measure 15 has a treble clef with eighth-note chords and a bass clef with a single note and a half rest. Measure 16 continues the treble line and has a bass clef with a half note and a half rest. Measure 17 has a treble clef with a whole rest and a bass clef with eighth-note chords.

18

Measures 18 and 19. Measure 18 has a treble clef with a half note and a half rest, and a bass clef with eighth-note chords. Measure 19 has a treble clef with a half note and a half rest, and a bass clef with eighth-note chords.

20

Measures 20, 21, and 22. Measure 20 has a treble clef with a half note and a half rest, and a bass clef with eighth-note chords. Measure 21 has a treble clef with a half rest and eighth-note chords in the bass. Measure 22 has eighth-note chords in both staves.

23

Measures 23 and 24. Measure 23 features a treble clef with eighth-note chords and a bass clef with a triplet of eighth notes. Measure 24 continues the treble line and has a bass clef with eighth-note chords. The piece concludes with a double bar line.